

THE MANGA GUIDE™ TO

# PHYSICS

COMICS  
INSIDE!

HIDEO NITTA  
KEITA TAKATSU  
TREND-PRO CO., LTD.

THE MANGA GUIDE™ TO PHYSICS



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THE MANGA GUIDE® TO PHYSICS



# THE MANGA GUIDE™ TO PHYSICS

HIDEO NITTA  
KEITA TAKATSU  
TREND-PRO CO., LTD.



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# PREFACE

It is essential to the understanding of physics to correctly “see” what you wish to examine. In classical mechanics, in particular, you need to understand how physical laws apply to transient, moving objects. But unfortunately, conventional textbooks rarely provide adequate images of such motion.

This book attempts to conquer the limits of those conventional textbooks by using cartoons. Cartoons are not just simple illustrations—they are an expressive and dynamic medium that can represent the flow of time. By using cartoons, it is possible to vividly express changes in motion. Cartoons can also transform seemingly dry laws and unreal scenarios into things that are familiar, friendly, and easy to understand. And it goes without saying—cartoons are fun. We have emphasized that in this book, as well.

As an author eager to know whether or not my intent has succeeded, I can only wait for readers to make their judgments. This work has been finished to my deep satisfaction, except for the omission of one chapter—due to page count constraints—featuring a trip to an amusement park to explain circular movement and the noninertial system.

The main character of this book is a high school student named Megumi Ninomiya who finds physics rather difficult. It is my sincere desire that this book reaches out to as many readers as possible who think “physics is tough” and who “don’t like physics,” helping them find pleasure in physics like Megumi does—even if it’s only a little.

Last but not least, I would like to express my deep appreciation to the staff at the OHM Development Office, scenario writer re\_akino, and illustrator Keita Takatsu—their combined efforts have resulted in this wonderful cartoon work that would have been impossible for one individual to complete.

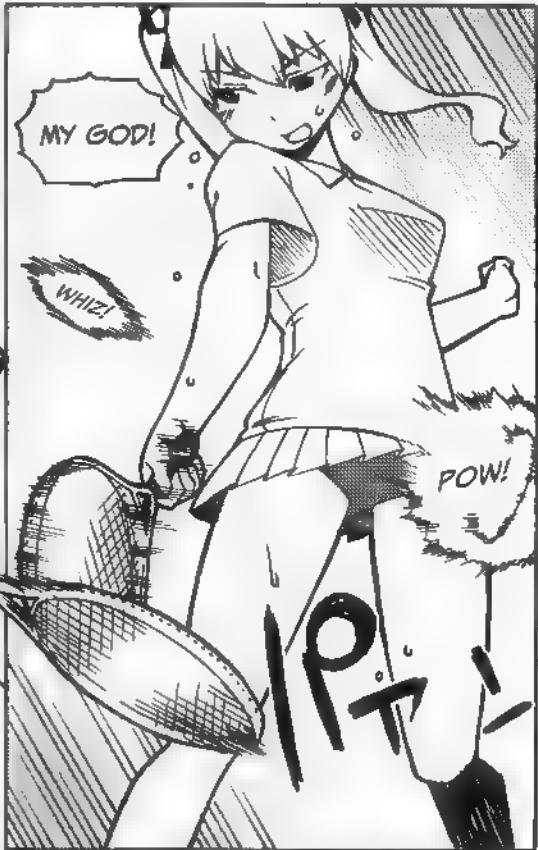
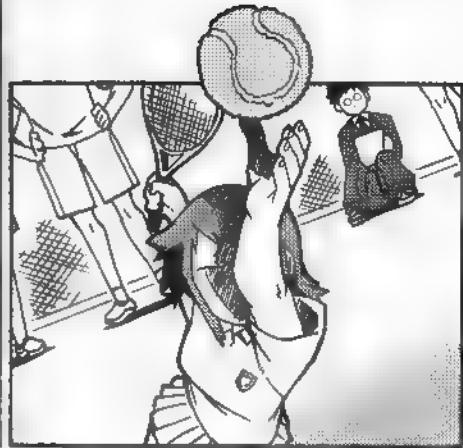
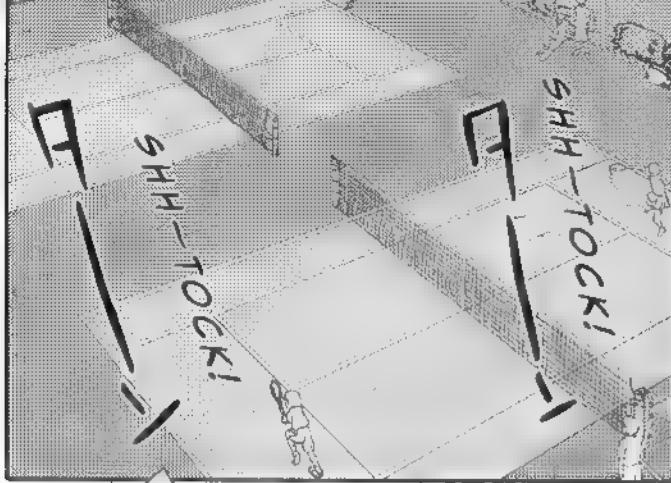
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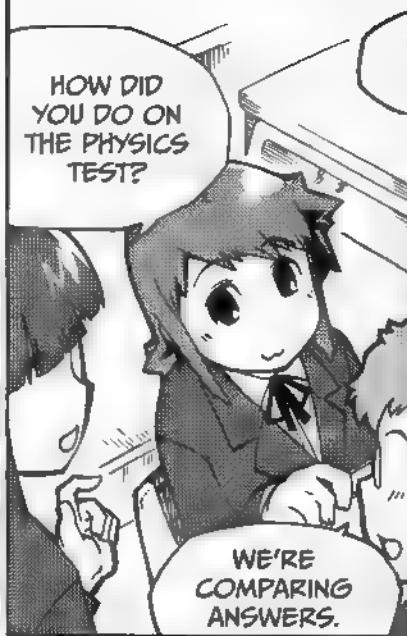


# PROLOGUE

DOES PHYSICS BOTHER YOU?







9) Suppose you are hitting a ball with a tennis racket. Which is greater, the force of the ball pushing the racket or the force of the racket pushing the ball? Select the correct answer.

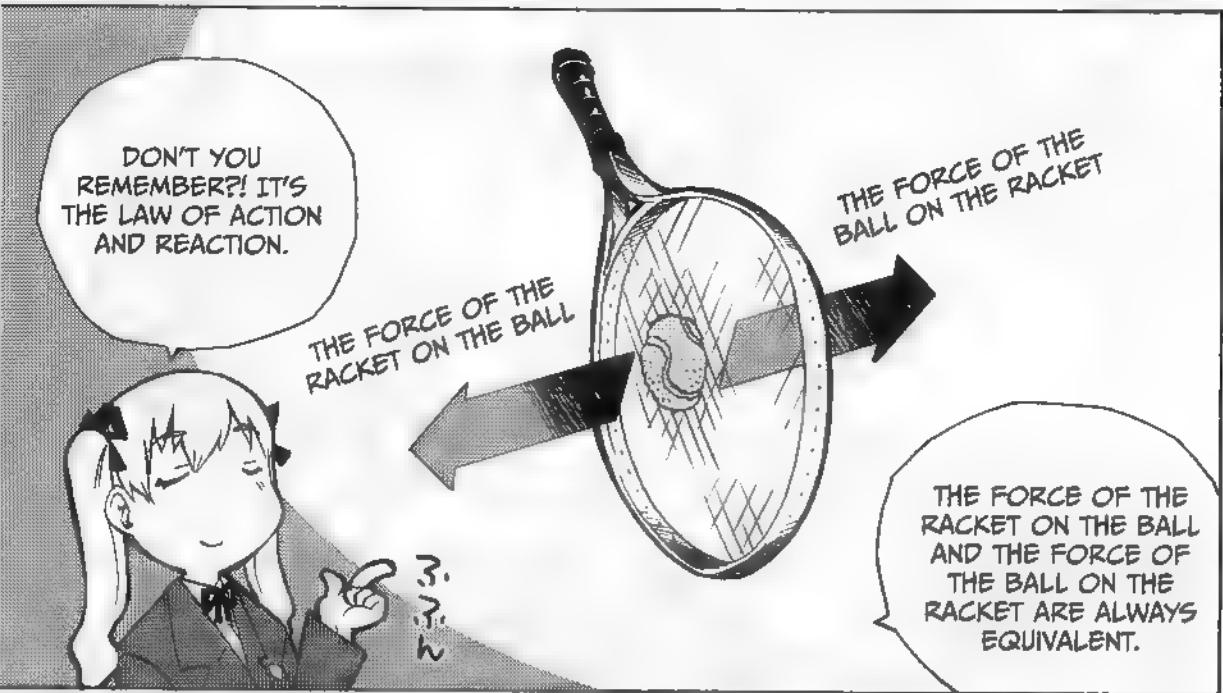
- A. The force of the racket pushing the ball is greater than the force of the ball pushing the racket.
- B. The force of the ball pushing the racket is greater than the force of the racket pushing the ball.
- C. The force of the ball pushing the racket is the same as the force of the racket pushing the ball.
- D. The relationship between the force of the ball pushing the racket and the force of the racket pushing the ball depends on the weight of the racket and the speed of the ball.

I SELECTED C.

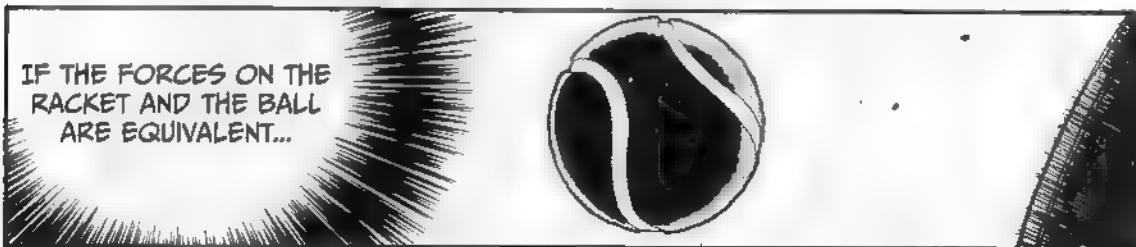
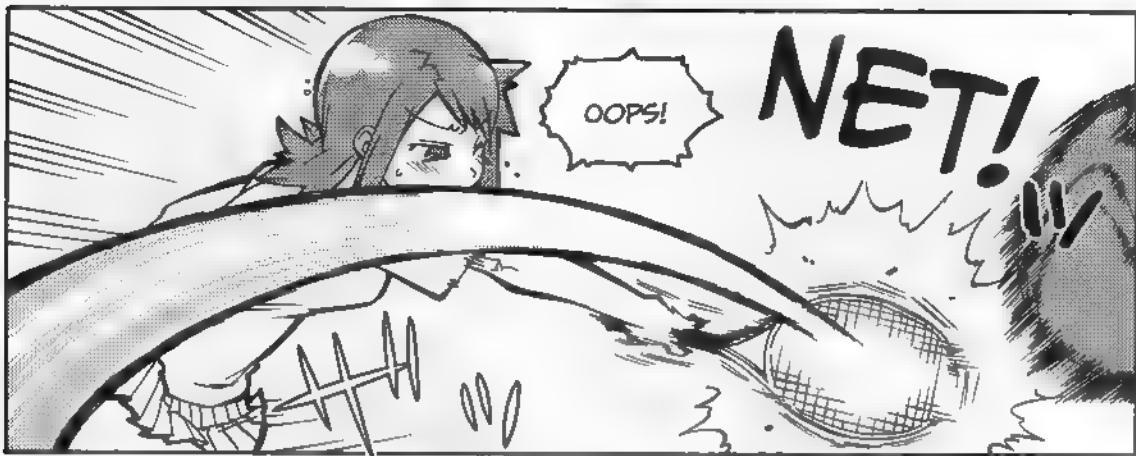
OH, NO...  
I PICKED A.

WHY?



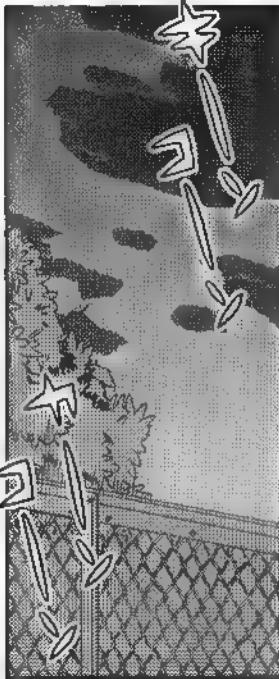








LATER THAT  
AFTERNOON...





BUT IT'S OKAY,  
SINCE IT WAS AN  
ACCIDENT.

WHAT ARE YOU  
DOING HERE,  
ANYWAY?

I WAS CALCULATING  
THE MOTION OF  
THE BALL WHILE  
WATCHING YOUR  
GAME.

THUMP  
THUMP

Magus.

$$\frac{m \cdot a}{m \cdot g} =$$

WOW! JUST LIKE A  
PHYSICS OLYMPICS  
SILVER MEDALIST  
WOULD!

SO...  
YOU SAW ME  
LOSE, TOO!

WELL,  
YEAH.

LISTEN!

LET ME TELL  
YOU WHY I LOST  
THAT GAME.

NUFF

WHAT DO  
YOU MEAN?

REMEMBER IN THE PHYSICS TEST WE HAD TODAY, THERE WAS A QUESTION ABOUT TENNIS.

SURE.

I GOT IT WRONG. THAT BOthered ME WHILE I PLAYED.

BOthered YOU?

YES.

MEGUMI EXPLAINS WHAT'S BEEN BOthering HER...

...I SEE.

NONOMURA-KUN, CAN YOU HELP ME UNDERSTAND PHYSICS?

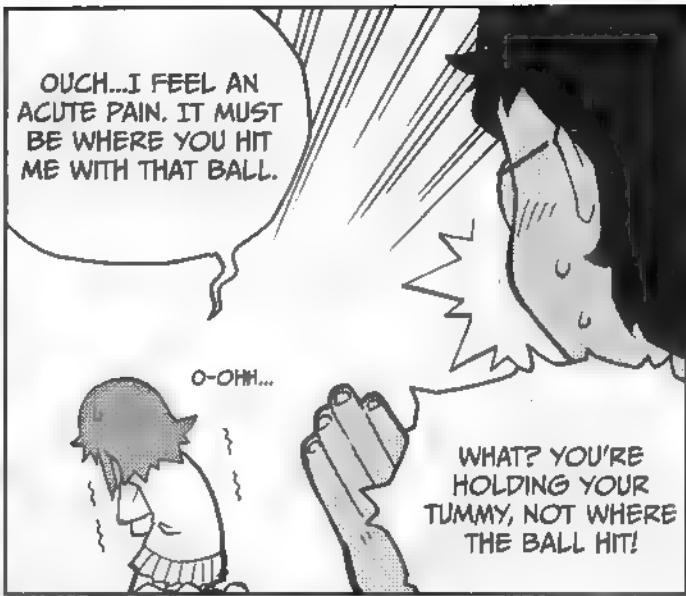
I COULDN'T CONCENTRATE ON THE GAME AT ALL.

CAN I ASK-

WHY ME...!?

WHA...?

YOU ARE A SILVER MEDALIST, AREN'T YOU? PLEASE HELP ME!





LAW OF ACTION  
AND REACTION



## LAW OF ACTION AND REACTION



\* LABORATORY



I HEAR A LOT  
ABOUT YOU, TOO,  
NINOMIYA-SAN,  
AS AN ALL-STAR  
ATHLETE.

NO KIDDING...?  
WELL, IT'S JUST  
WHAT I LIKE,  
YOU KNOW.

WELL, THEN,  
PLEASE STUDY  
PHYSICS AS MUCH  
AS YOU PRACTICE  
SPORTS.

I WILL! AND  
THANK YOU  
FOR YOUR  
HELP!

HOW THE LAW OF ACTION AND  
REACTION WORKS

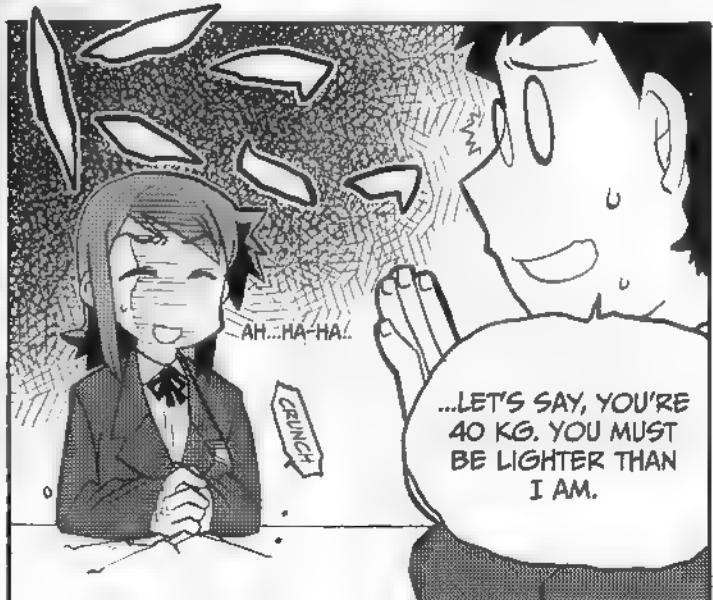
NOW, LET'S GET  
STARTED.

YOU WANT TO LEARN  
ABOUT THE LAW OF  
ACTION AND REACTION,  
RIGHT?

YES, I DO.

AT LEAST THAT'S WHAT  
SAYAKA MENTIONED...

BEFORE WE THINK  
ABOUT IT USING  
A RACKET AND A  
BALL...





LET'S TRY IT THE  
OPPOSITE WAY.

IF I PUSH, BOTH  
OF US WILL MOVE  
BACKWARD AGAIN.

REALLY?

WHEN YOU  
ATTEMPT TO USE  
FORCE ON ME,

EVEN IF I DON'T  
MEAN TO PUSH  
YOU BACK,

FORCE WILL  
BE APPLIED TO  
YOUR BODY,  
NINOMIYA-SAN.

HOWEVER AND  
WHENEVER EITHER  
OF US APPLIES  
FORCE TO THE  
OTHER,

SHAZAM!

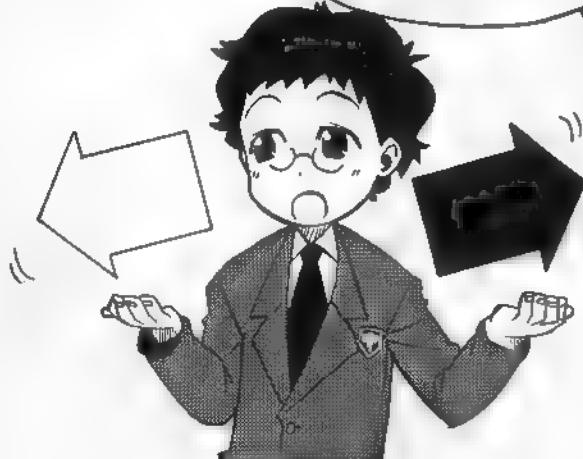
THE OTHER ONE  
WILL RECEIVE THE  
SAME FORCE IN  
THE OPPOSITE  
DIRECTION.

AHA.

SO I CAN'T  
MOVE YOU  
WITHOUT BEING  
MOVED MYSELF.

IN ADDITION, THE MAGNITUDE OF THE FORCE IS ALWAYS THE SAME ON BOTH SIDES.

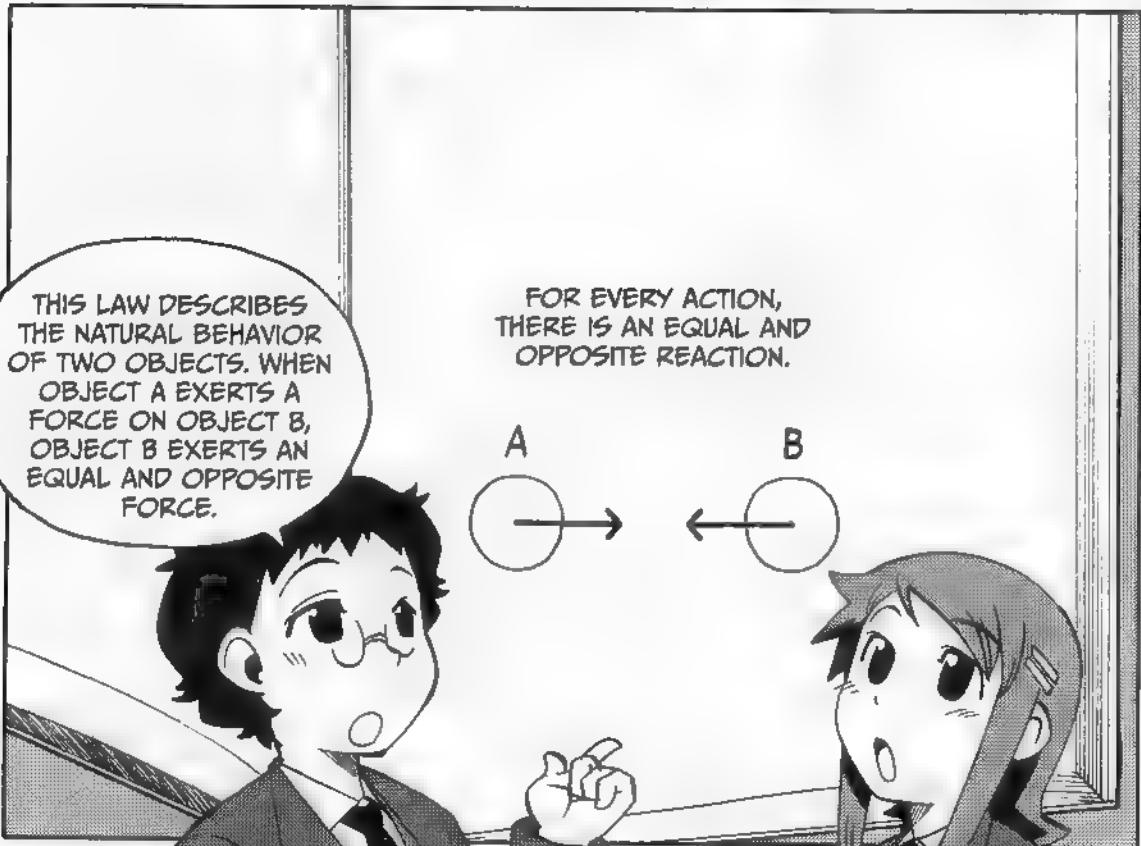
THIS IS CALLED THE LAW OF ACTION AND REACTION, AND IT ALSO EXPLAINS WHY FORCE IS ALWAYS GENERATED BETWEEN A PAIR OF OBJECTS.

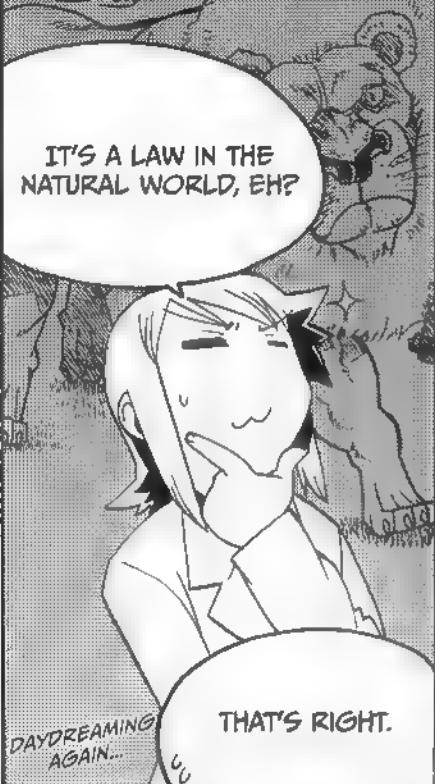


THAT'S NEWS TO ME.

HMM...

WE CAN SUMMARIZE IT CLEARLY AS FOLLOWS:





WHEN OBJECTS  
ARE STATIC, IT'S  
EASY TO MIX  
UP THE LAW OF  
ACTION AND  
REACTION

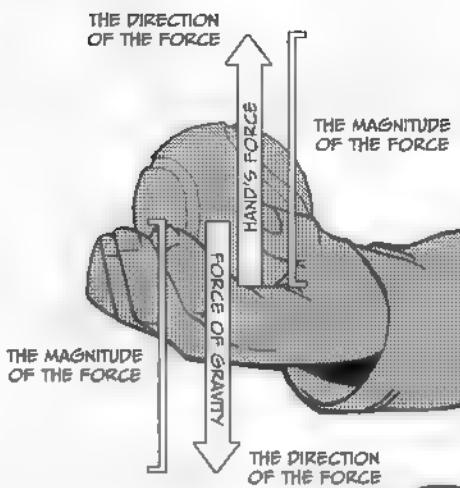
WITH  
EQUILIBRIUM,  
OR A BALANCE  
OF FORCES.

BALANCE...OF  
FORCES?

LET ME ILLUSTRATE  
THE FORCE APPLIED  
TO A BALL IN THE  
PALM OF MY HAND.

FORCE HAS A  
DIRECTION IN ADDITION  
TO A MAGNITUDE.

A QUANTITY HAVING  
A MAGNITUDE AND  
DIRECTION IS CALLED  
A VECTOR.



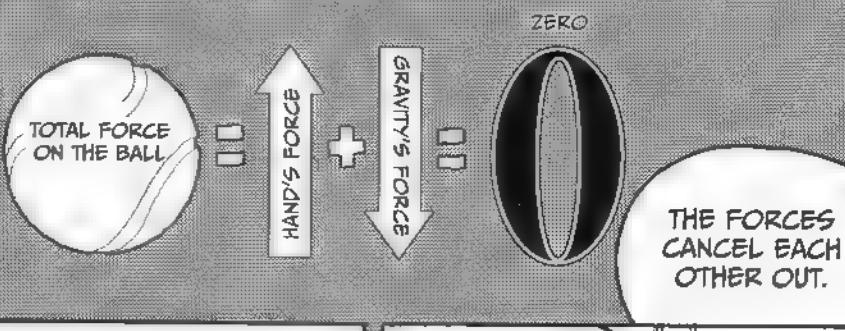
AS REPRESENTED  
BY THE ARROWS  
IN YOUR  
ILLUSTRATION, I  
SUPPOSE.

DRAW AN ARROW THAT POINTS IN THE DIRECTION OF THE FORCE, WITH ITS LENGTH REPRESENTING THE MAGNITUDE.

SO THE ILLUSTRATION SHOWS...



YES. EQUILIBRIUM REFERS TO A RELATIONSHIP OF FORCES LIKE WHAT YOU SEE IN THIS ILLUSTRATION.



THE FORCES CANCEL EACH OTHER OUT.

IF I WITHDRAW MY HAND QUICKLY TO STOP SUPPORTING THE BALL,

IT'S GONE!



NOW GRAVITY IS THE ONLY FORCE ACTING ON THE BALL, SO IT FALLS.



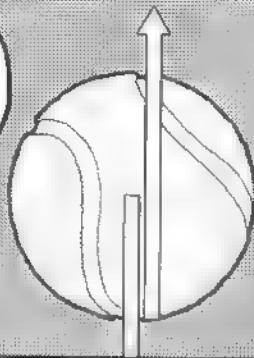
WHIN



## EQUILIBRIUM VS. LAW OF ACTION AND REACTION



THE CONCEPT OF EQUILIBRIUM INVOLVES FORCE APPLIED TO A SINGLE OBJECT.



AHA!

SO THAT'S THE DIFFERENCE BETWEEN EQUILIBRIUM AND THE LAW OF ACTION AND REACTION.

ON THE OTHER HAND, THE LAW OF ACTION AND REACTION INVOLVES FORCES AFFECTING SEPARATE OBJECTS LIKE THE BALL AND THE HAND.



WHEN YOU HOLD A BALL, YOU FEEL THE WEIGHT OF THE BALL, DON'T YOU?

THAT'S THE EVIDENCE THAT YOUR HAND IS ALSO PUSHING THE BALL WITH A FORCE OF THE SAME MAGNITUDE...

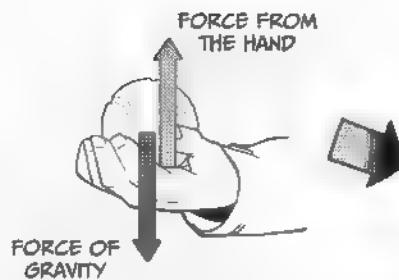
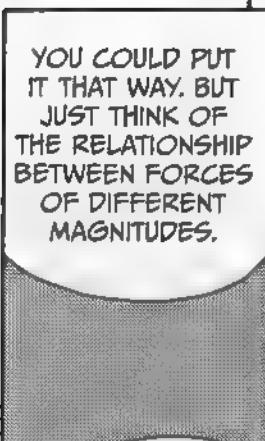
AS THE FORCE FROM THE BALL PUSHING YOUR HAND. SO THAT'S THE LAW OF ACTION AND REACTION.

IT INVOLVES A DIFFERENT VIEWPOINT FROM THE CONCEPT OF EQUILIBRIUM.



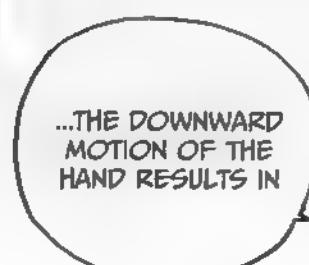
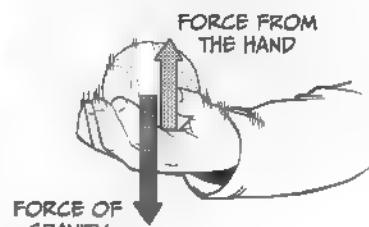


YOU'VE JUST WITNESSED A STATIC OBJECT THAT STARTED MOVING. CAN YOU EXPLAIN WHY?



STATIC STATE  
(THE FORCES ARE BALANCED.)

WHEN THE HAND GOES DOWN...



AM I...  
AM I RIGHT?

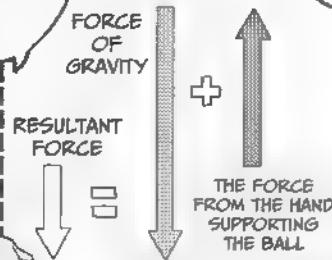
WHOOPEE!

EXACTLY!  
YOU'VE GOT IT.

AS THE FORCE FROM  
THE HAND APPLIED TO  
THE BALL BECOMES  
SMALLER, THE BALANCE  
OF FORCES IS BROKEN,  
AND A GREATER  
DOWNWARD FORCE  
EMERGES.

FROM THE VIEWPOINT  
OF EQUILIBRIUM, WE CAN  
EXPLAIN THE FALLING OF  
A BALL THAT WAY.

GOING  
DOWN,  
SIR.



THE FORCE  
FROM THE HAND  
SUPPORTING  
THE BALL

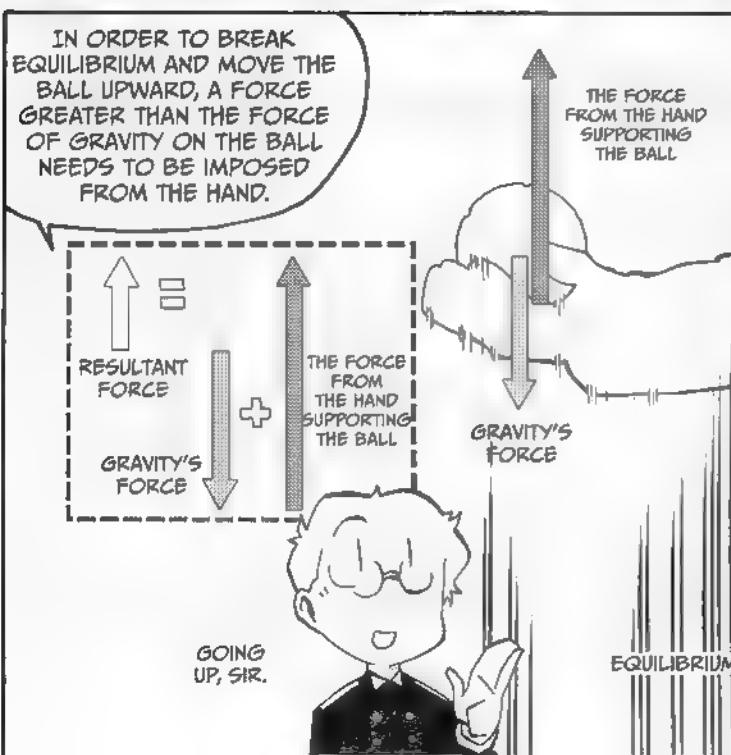
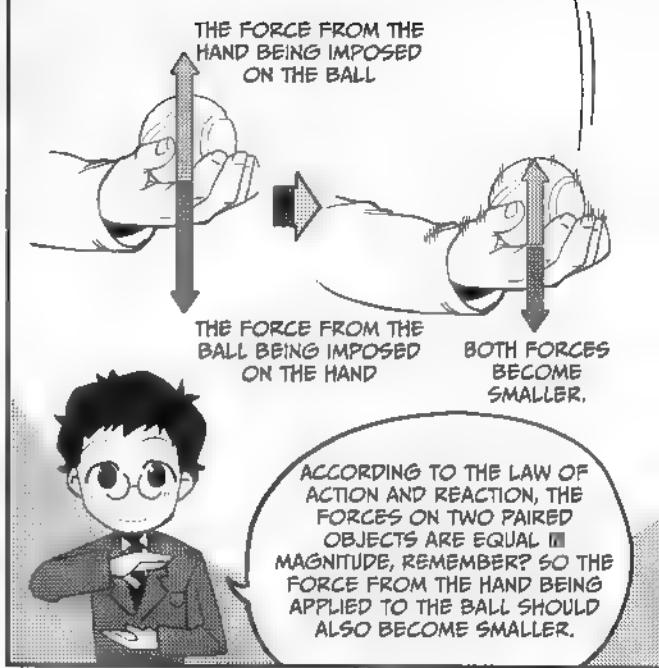
SO THE BALL IS  
NO LONGER IN  
EQUILIBRIUM.

NOW WHAT WOULD  
IT LOOK LIKE WHEN  
VIEWED FROM A  
STANDPOINT OF THE  
LAW OF ACTION AND  
REACTION?

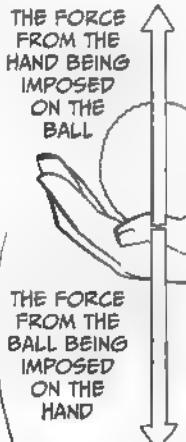
SO WE TAKE  
BOTH THE BALL  
AND THE HAND  
INTO ACCOUNT.

EXACTLY! WHEN  
YOU LOWER YOUR  
HAND, HOW DOES  
THE WEIGHT OF THE  
BALL FEEL?





THEN THE RESULTING REACTION FORCE BECOMES GREATER, TOO. THAT'S WHY YOU NOTICE IT FEELS HEAVIER.



YOU SEE, THE FORCE FROM THE BALL IMPOSED ON THE HAND INCREASES JUST AS MUCH AS THE FORCE FROM THE HAND IMPOSED ON THE BALL INCREASES.

NOW DOES THIS HELP YOU UNDERSTAND THE EXAM QUESTION INVOLVING A RACKET AND A BALL?

FLASH BACK

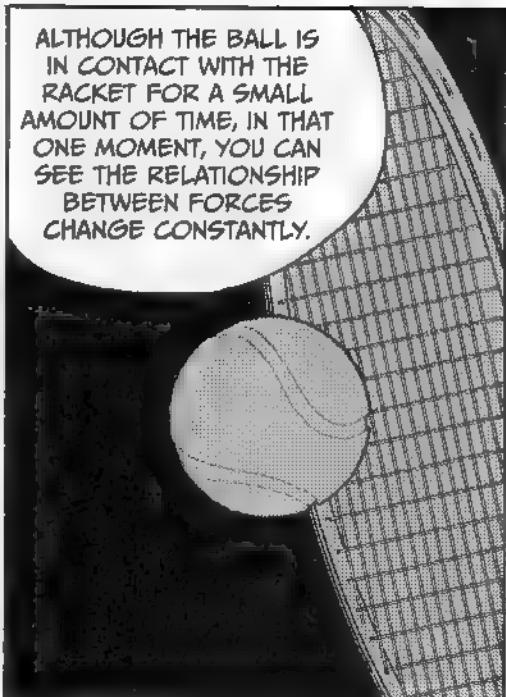
UMMM...

NONE OF YOUR BUSINESS!

WHAT'S THE MATTER WITH YOU, NINOMIYA-SAN?

AHEM. SORRY. I THINK THE QUESTION WENT LIKE THIS.

9) Suppose you are hitting a ball with a tennis racket. Which is greater, the force of the ball pushing the racket or the force of the racket pushing the ball?



SO, IF YOU LOOK AT EACH MOMENT AS IF TIME WERE STOPPED, IT IS JUST LIKE WHEN A BALL SITS STILL ON YOUR PALM.

THAT'S RIGHT.

YOU CAN ALWAYS FIND THE LAW OF ACTION AND REACTION EITHER IN MOTION OR IN STATIC STATES.

GET IT?



THANKS.

AT LAST, I FULLY UNDERSTAND IT.

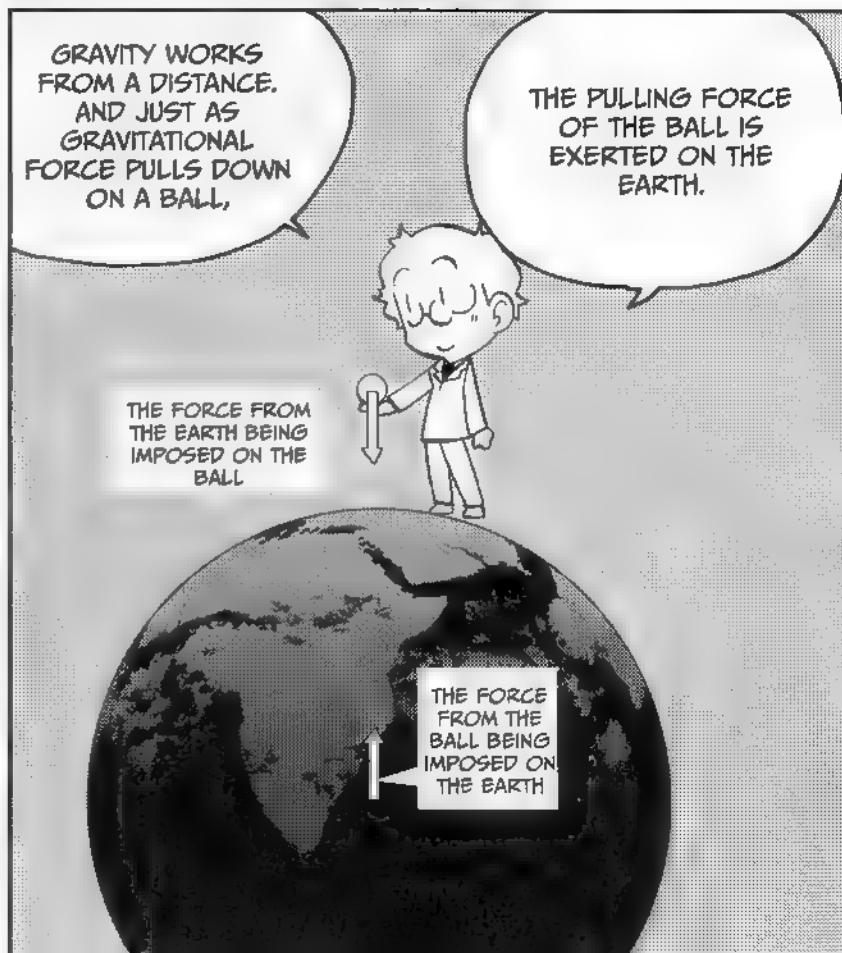
THAT'S GOOD.

WAIT.

### GRAVITATIONAL FORCE AND THE LAW OF ACTION AND REACTION

ACCORDING TO THE LAW OF ACTION AND REACTION, YOU SAID FORCES ARE ALWAYS GENERATED IN PAIRS.

YEAH, THAT'S RIGHT...



THE BALL IS  
PULLING THE  
EARTH?

SURE.  
BECAUSE  
THEY MAKE  
A PAIR.

ANY OBJECTS THAT  
HAVE MASS ARE  
PULLING EACH  
OTHER IN THE FORM  
OF UNIVERSAL  
GRAVITATION.

IT'S HARD TO  
BELIEVE THAT  
A BALL IS  
PULLING...

WELL, A BALL COULD  
NEVER MOVE THE  
EARTH, SINCE THE  
MASS OF THE EARTH  
IS TREMENDOUS.

I SEE.

SO, UNIVERSAL  
GRAVITATION MUST BE  
WORKING BETWEEN  
YOU, NONOMURA-KUN,  
AND ME, CAUSING US TO  
GET CLOSER.

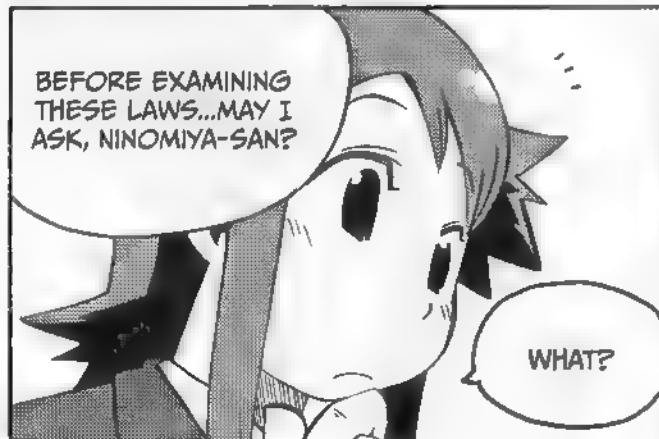
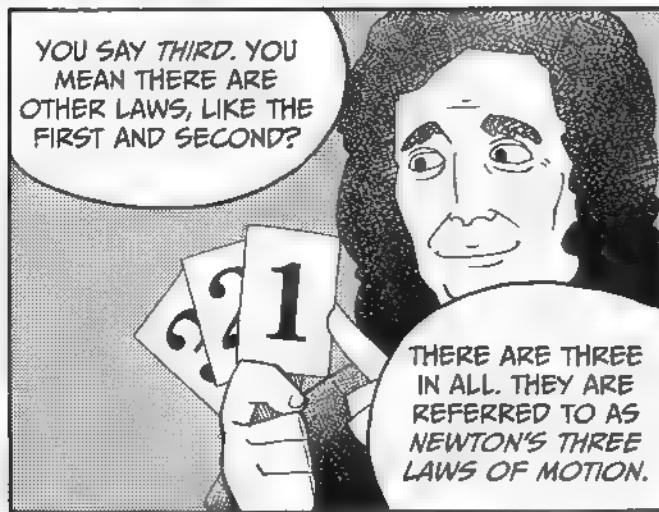
WHAT HAPPENED TO  
YOUR PROMISE TO  
TRY TO UNDERSTAND  
SERIOUSLY?

OOPS! HOW  
EMBARRASSING!

...UNIVERSAL  
GRAVITATION IS  
PROPORTIONATE  
TO THE PRODUCT  
OF MASSES OF  
ELEMENTS PULLING  
EACH OTHER.

THE MASS OF A  
PERSON IS EXTREMELY  
SMALL, SO UNIVERSAL  
GRAVITATION CANNOT  
BE FELT BETWEEN  
PEOPLE!

## NEWTON'S THREE LAWS OF MOTION



MEMORIZING LOTS  
OF EQUATIONS  
FOR TESTS.  
I USED TO SEE  
IT THAT WAY.



SO, MAYBE IT'S TO  
HELP UNDERSTAND  
THE MECHANICS OF  
MOTION. RIGHT?

THAT'S GREAT.

BUT AFTER  
LISTENING TO YOUR  
EXPLANATION,  
NONOMURA-KUN,  
MY VIEW MAY HAVE  
CHANGED A LITTLE.

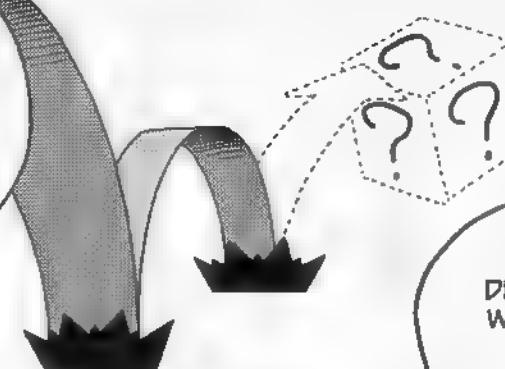
PHYSICS SHOULDN'T  
BE LEARNED BY  
ROTE.

IN MY OPINION,  
PHYSICS MEANS,  
"EXPLAINING  
NATURAL  
PHENOMENA  
USING LAWS—

OR PREDICTING  
THEM BASED ON  
MATHEMATICAL DATA."

WOW! THAT'S  
CONVINCING  
ENOUGH.

AND THE  
FOUNDATION OF  
PHYSICS IS CLASSICAL  
MECHANICS—WHAT  
WE'RE STUDYING IN  
CLASS.



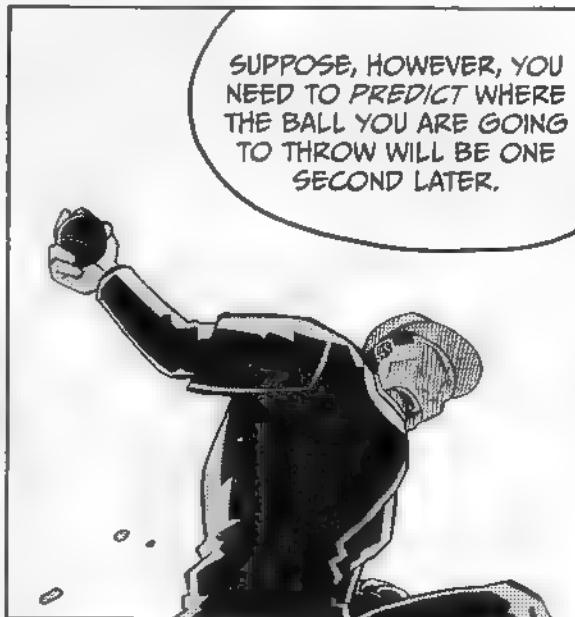
THE OBJECTIVE OF PHYSICS IS TO PREDICT THE MOTION OF AN OBJECT. IN OTHER WORDS, WE LEARN PHYSICS IN ORDER TO CORRECTLY TELL WHEN AND WHERE THAT OBJECT WILL BE.

IT SOUNDS DIFFERENT FROM WHAT I THOUGHT BEFORE.

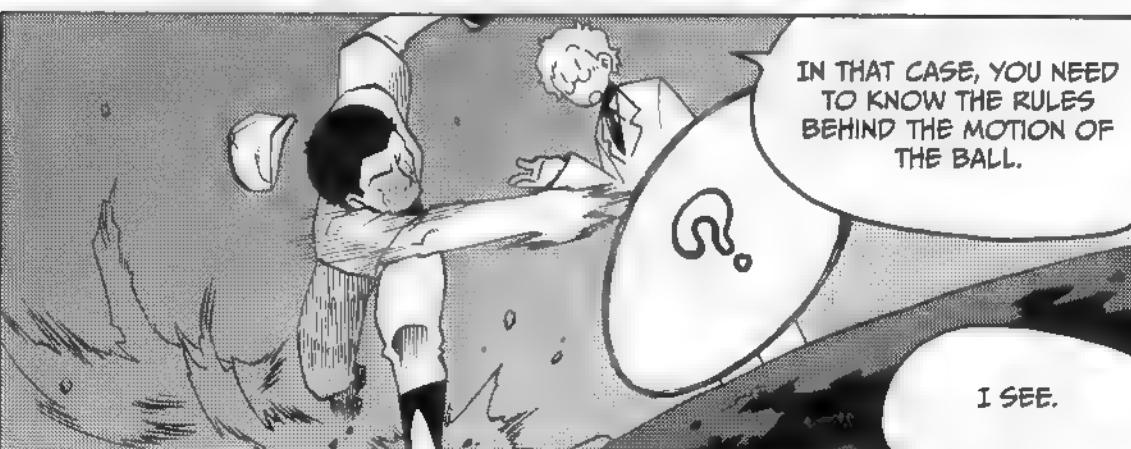


IT'S EASY TO TAKE A VIDEO OF A MOVING BALL AND SEE WHERE IT WAS AT A PARTICULAR TIME, ISN'T IT?

I GUESS...

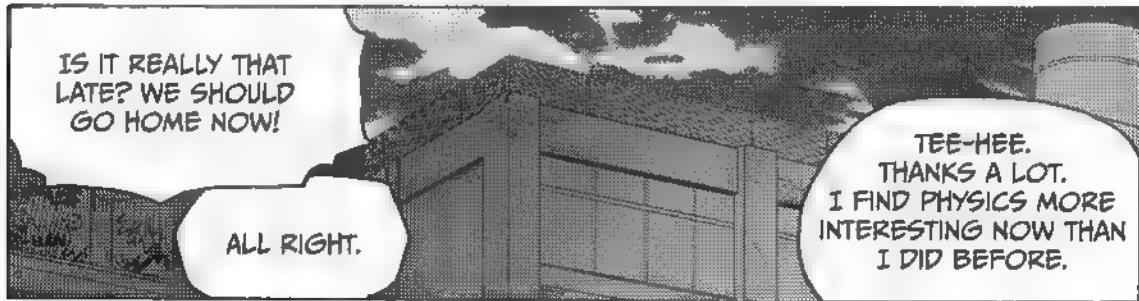


SUPPOSE, HOWEVER, YOU NEED TO PREDICT WHERE THE BALL YOU ARE GOING TO THROW WILL BE ONE SECOND LATER.



IN THAT CASE, YOU NEED TO KNOW THE RULES BEHIND THE MOTION OF THE BALL.

I SEE.



# SCALAR QUANTITIES VS. VECTOR QUANTITIES

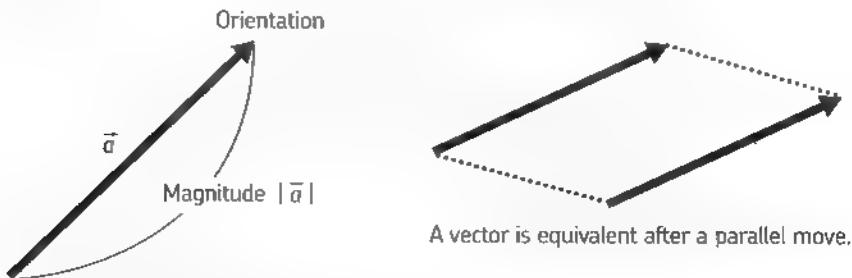


Physics involves measuring and predicting various quantities (or physical values) like force, mass, and velocity. These values can be classified into those having only magnitude and those having both magnitude and direction. A quantity that has magnitude without a direction is referred to as a *scalar* quantity. Mass is a scalar quantity. Energy and work, which we'll learn about in Chapter 4, are also scalar quantities.

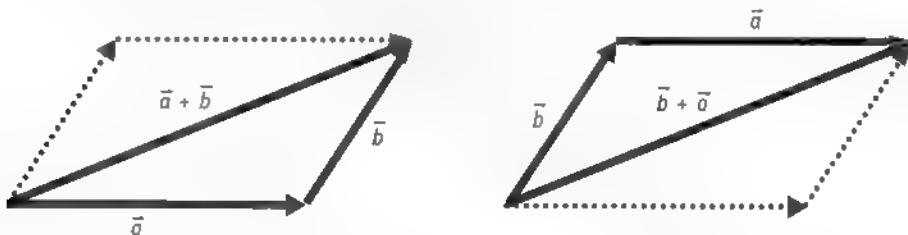
On the other hand, force is a value with a direction. You can see that from the fact that the motion of an object changes if you apply force from a different direction. A quantity that has a direction is called a *vector*. Velocity and acceleration (which are introduced in Chapter 2) and momentum (discussed in Chapter 3) are also vector quantities, as they have direction. You may forget the terms *scalar* and *vector*, but you should keep in mind that there are two types of values in physics: those with just a magnitude and those with both a magnitude and a direction.

## VECTOR BASICS

A vector is represented using an arrow. The length of the arrow represents the magnitude of the vector, and the point represents its orientation, or direction. Two vectors with the same magnitude and direction are equivalent to one another, even if they do not have the same origin.



Also note that the magnitude of a vector (represented by the length of the arrow) can be noted with absolute value symbols, like  $|\vec{a}|$ , or simply as  $a$ .



The sum of two vectors ( $\vec{a} + \vec{b}$ ) is shown by joining the head of vector  $\vec{a}$  to the tail of vector  $\vec{b}$ , and then extending a line from the tail of  $\vec{a}$  to the head of  $\vec{b}$ , as shown in the

figure on the left here. As this vector is a diagonal of the parallelogram in the figure, it is obvious that it is also equivalent to  $\vec{b} + \vec{a}$ . Therefore, we know that the following is true:

$$\text{COMMUTATIVE LAW: } \vec{a} + \vec{b} = \vec{b} + \vec{a}$$

The order in which you add vectors doesn't matter! You can find the sum of three or more vectors in the same way.

## NEGATIVE VECTORS

Vector  $-\vec{a}$ , or  $\vec{a}$  preceded by a minus sign, yields a sum of zero when added to vector  $\vec{a}$ . In an equation, the relationship looks like this:

$$\vec{a} + (-\vec{a}) = 0$$

In terms of geometry,  $-\vec{a}$  is simply a vector of the same magnitude as  $\vec{a}$ , but in the exact opposite direction. The 0 on the right side of this equation represents zero as a vector, referred to as a *zero vector*. When vectors cancel each other out in this way, an object is said to be in *equilibrium*.

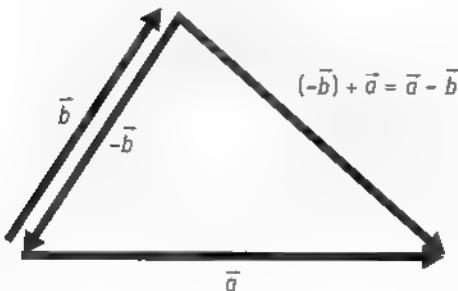


## DIFFERENCE BETWEEN TWO VECTORS

The difference between two vectors ( $\vec{a} - \vec{b}$ ) can be defined as follows:

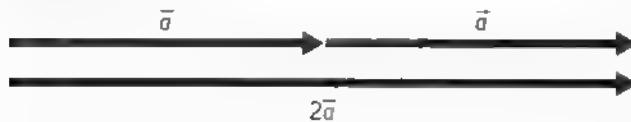
$$\vec{a} - \vec{b} = \vec{a} + (-\vec{b})$$

Thus, we can find the result of the equation using the same process for summing vectors.



## MULTIPLYING VECTORS BY SCALARS

Doubling vector  $\vec{a}$  means doubling its magnitude without changing its direction. The result is represented as  $2\vec{a}$ .



Generally,  $k$  multiplied by  $\vec{a}$  ( $k\vec{a}$ ) represents a vector with a magnitude  $k$  times greater than  $\vec{a}$  but in the same direction.

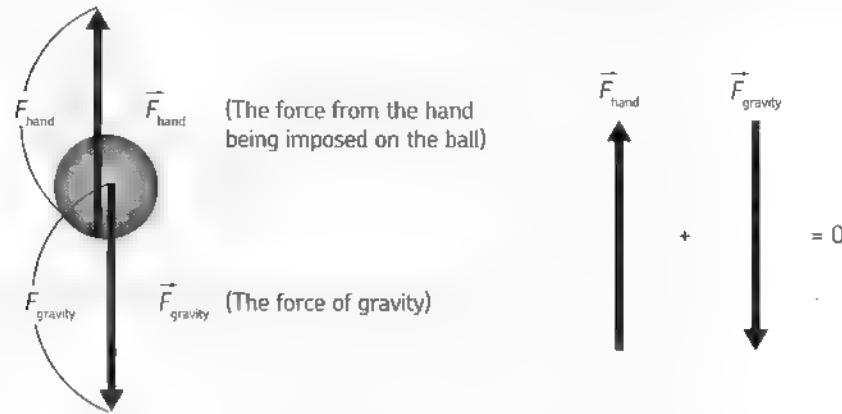
## EQUILIBRIUM AND VECTOR FORCES



In discussing the total forces on the tennis ball on page 22, we saw the following equation:

$$\text{total force on the ball} = \text{force of gravity} + \text{force from the hand} = 0$$

Do you think the plus sign is an error and there should be a minus sign there instead? It's not an error! Remember that forces are vectors—this equation is true as is. Considered as vectors, the total forces working on an object must equal the sum of all the forces.



Let's look into the balance between the forces on the ball and the hand holding it. Let's call the force from the hand on the ball  $\vec{F}_{\text{hand}}$  and the force of gravity on the ball  $\vec{F}_{\text{gravity}}$ . The resultant force ( $\vec{F}_{\text{resultant}}$ ) acting on the ball is expressed as follows:

$$\vec{F}_{\text{resultant}} = \vec{F}_{\text{hand}} + \vec{F}_{\text{gravity}}$$

The resultant force is also called the *net force*. If the forces on a ball are balanced, it means the resultant force has reached zero:

$$\vec{F}_{\text{resultant}} = 0 \text{ or, to put it another way, } \vec{F}_{\text{hand}} + \vec{F}_{\text{gravity}} = 0$$

Yes, that's exactly it. In short,  $\vec{F}_{\text{hand}}$  and  $\vec{F}_{\text{gravity}}$  are vectors of the same magnitude in opposite directions, resulting in zero when added:

$$\text{the force exerted by the hand on the ball} + \text{force of gravity on the ball} = \text{zero}$$

Now, let's look at forces in terms of magnitude only, not as vectors with direction. As explained on page 37, the magnitude of a force is expressed as  $|\vec{F}_{\text{hand}}|$  or  $|\vec{F}_{\text{gravity}}|$ , using absolute value symbols. Developing these expressions further, you get equations like  $|\vec{F}_{\text{hand}}| = F_{\text{hand}}$  and  $|\vec{F}_{\text{gravity}}| = F_{\text{gravity}}$ . Now you know the two forces have an equivalent magnitude, which can be expressed as follows in an equation for a subtraction:

$$F_{\text{hand}} = F_{\text{gravity}} \text{ or } F_{\text{hand}} - F_{\text{gravity}} = 0$$

Note that these forces are represented without arrows, which indicates that they are magnitudes. When giving equations for balanced forces, we need to make a clear distinction between cases where forces are considered to be vectors and cases where they are considered to be simple magnitudes without direction (scalars).

## NEWTON'S THREE LAWS OF MOTION



Isaac Newton was an English physicist born in 1643. Based on his observations of motion, he developed the following laws.

**The first law (law of inertia):** A body at rest tends to stay at rest unless acted upon by an outside net force. A body in motion tends to stay in motion at a constant velocity unless acted on by an outside net force.

**The second law (law of acceleration):** The net force on an object is equal to the mass of the object multiplied by its acceleration.

**The third law (law of action and reaction):** For every action there is an equal and opposite reaction.

Let me explain in terms of the ball held in my hand in this chapter. (We'll discuss this further in Chapter 2.)

Given the first law, we can tell that the total forces on a static object have reached zero in magnitude. Because the ball is in a state of equilibrium, it is static and remains so; this is the first law of motion in action. Because the ball is not moving, there must be no resultant force from the sum of the force of my hand and the force of gravity.

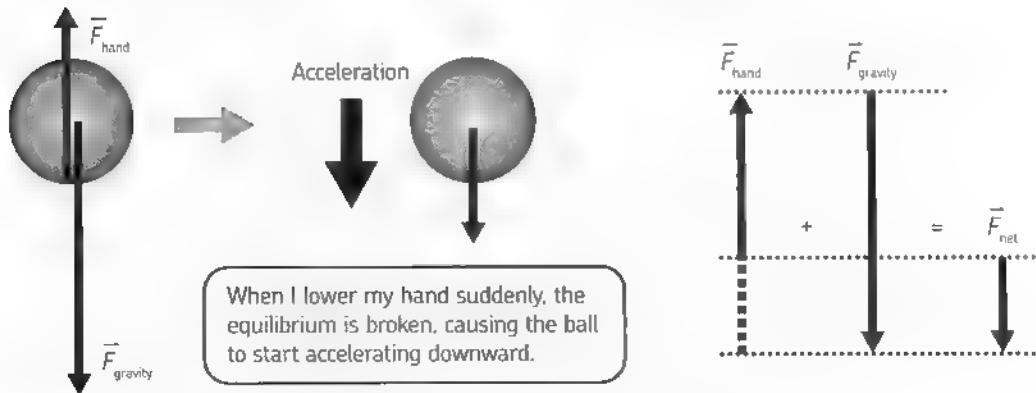
As we learned in this chapter, the law of action and reaction is the third law of motion. This law tells us that the force from the hand acting on the ball and the force from the ball acting on the hand are equivalent in magnitude and opposite in direction. The law of action and reaction is always present. It is also working when you keep a ball in motion by moving your hand.

The second law of motion tells us that an object receiving a net force begins moving with acceleration. If you suddenly lower your hand while holding a ball, the force from the hand on the ball ( $F_{\text{hand}}$ ) suddenly decreases in magnitude, but the force of gravity on the

ball ( $\vec{F}_{\text{gravity}}$ ) stays the same. Therefore, the balance of forces is broken, and the sum of  $\vec{F}_{\text{gravity}}$  and  $\vec{F}_{\text{hand}}$  on the ball attains a nonzero value while the ball is moving. Thinking in terms of magnitude:

$$F_{\text{net}} = F_{\text{gravity}} - F_{\text{hand}} > 0$$

The above equation represents the magnitude of the force applied downward. At this time, given the second law of motion, which states that an object receiving a force attains acceleration proportional to that net force, the ball should begin accelerating, or start moving. This is how mechanics explains the motion of a ball caused when the hand retaining it is suddenly lowered. This same idea can be applied when a ball is suddenly lifted.



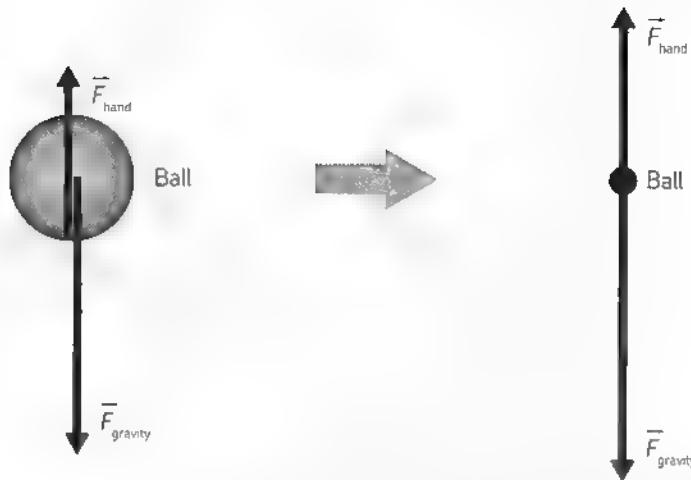
There is one thing you need to keep in mind. When a ball moves up and down at a constant speed, you should note that the net force (resultant force) on the ball remains zero, as the forces are balanced: the ball is not accelerating. The first law of motion tells us that. A nonzero net force is acting on the ball when the speed of the object's motion varies or any acceleration occurs. When the object moves at a constant speed, the acceleration is zero, and so is the net force. In other words, the forces applied are balanced, even though the ball is moving.

A force must be applied to an object for it to begin moving from a static state. Starting motion means the object transitions from a zero-velocity state to one with a velocity. When this occurs, the object has accelerated.

## DRAWING A FREE-BODY DIAGRAM

In the figure showing vectors of forces acting on a ball in the previous section,  $\vec{F}_{\text{hand}}$  and  $\vec{F}_{\text{gravity}}$  have different starting points. Physicists call drawings like this *free-body diagrams*. When you draw a vector to represent the force of the hand on the ball, you start it at the point where the two come into contact with each other. That's not so confusing, but why do you think the starting point for gravity is located at the center of the ball?

In basic physics, an object is treated as a point of mass without a volume; it doesn't matter where the vector starts. We draw that mass point as an object with a certain volume simply because it is easier to see that way in a figure or illustration.



Let's consider an object with volume, and how we can represent forces imposed on it. In the case of a ball on my hand, the force of gravity is imposed on the center of the ball's mass (which also called the *center of gravity*). You can see in the diagram above that this is where the force vector is acting. However, the upward force of my hand is acting on the outside of the ball, as that is the point of contact. We'll draw the force vector starting there in our diagram.

But to simplify our calculations, we'll treat this object as a mass without volume—that is, a single point with mass. We'll simplify all objects with volume similarly, as the calculations for objects with volume can become very complicated. A diagram that represents this simplified free-body diagram is on the right. Bear in mind that we will simplify all the examples in this book in this way in our calculations, even if our diagrams appear more complex.

## EXPRESSING NEWTON'S THIRD LAW WITH AN EQUATION

To express the law of action and reaction in correct wording, we need a lengthy phrase like "When an object impacts another object, both objects receive a force of the same magnitude but in opposite directions." So let's try to express the law of action and reaction as a simple equation instead. When object A imposes force  $\vec{F}_{A \rightarrow B}$  on object B and object B imposes force  $\vec{F}_{B \rightarrow A}$  on object A, the law of action and reaction is expressed as follows:

$$\vec{F}_{A \rightarrow B} = -\vec{F}_{B \rightarrow A}$$

So, you can express the law in a single equation, as shown above. In fact, comparing the elements in this equation in terms of absolute values, you get:

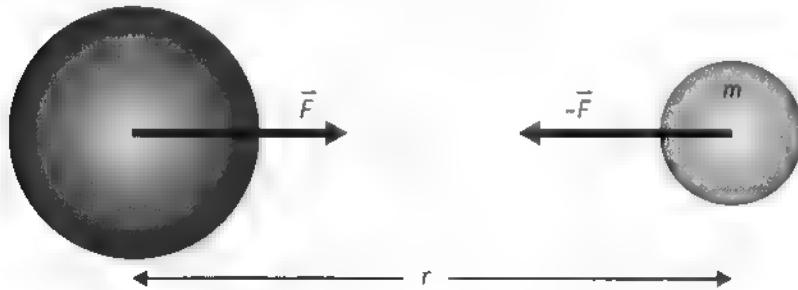
$$|\vec{F}_{A \rightarrow B}| = |\vec{F}_{B \rightarrow A}|$$

Now you can see that the action and the reaction are equivalent in magnitude, and the minus sign tells you that their directions are opposite. Using equations can help you express Newton's laws in a simpler and more precise manner than verbal expression.

## GRAVITY AND UNIVERSAL GRAVITATION



In the narrowest sense of the term, gravity is the force of the earth attracting objects toward itself. But the force of the earth comes from universal gravitation between all objects of mass, not just the earth itself. Between two objects, there is an attractive force proportional to the product of the objects' masses and inversely proportional to the distance between them, raised to the second power. This attractive force is *universal gravitation*, as discovered by Newton. It's called *universal* gravitation because it works on *all* objects with mass—it's not affected by the type of object. Its value only depends on the mass of objects affecting each other and the distance between them.



As shown in the figure, when two objects with mass  $M$  and mass  $m$  are separated from each other by distance  $r$ , a force of  $F$  attracts the two objects. The equation is as follows:

$$F = G \frac{mM}{r^2}$$

$G$  is a universal constant referred to as the *universal gravitational constant*:

$$G = 6.67 \times 10^{-11} \text{ (N} \times \text{m}^2/\text{kg}^2\text{)}$$

For an explanation of the unit newton (N), see page 92.

Universal gravitation satisfies the law of action and reaction, as it exerts a force on both masses  $M$  and  $m$ . The equation above can be used to calculate the force on either object. As their directions are obviously opposite, they satisfy the law of action and reaction. Thus, we should note that forces working between objects at a distance from each other (not just objects that come into contact with each other) also satisfy the law of action and reaction.

Universal gravitation is a very small force compared to electromagnetic force. While electromagnetic forces may be attractive or repulsive depending on a combination of positive and negative charges, universal gravitation always works as attractive force—that is, objects are always drawn closer to each other.

Because of universal gravitation, cosmic dust in outer space gathers into giant masses over time—such as the earth or the other planets.

Carolina Pezzano D'A



## FORCE AND MOTION

## VELOCITY AND ACCELERATION

### SIMPLE MOTION



BEFORE WE CAN UNDERSTAND THE LAWS OF MOTION, WE NEED TO KNOW WHAT VELOCITY AND ACCELERATION ARE. FIRST, LET'S TALK ABOUT VELOCITY. TO GET THE SIMPLEST IDEA OF VELOCITY,



WE SHOULD THINK ABOUT THE MOTION OF AN OBJECT WHEN IT MOVES STRAIGHT AT A CONSTANT SPEED.

UHMM...

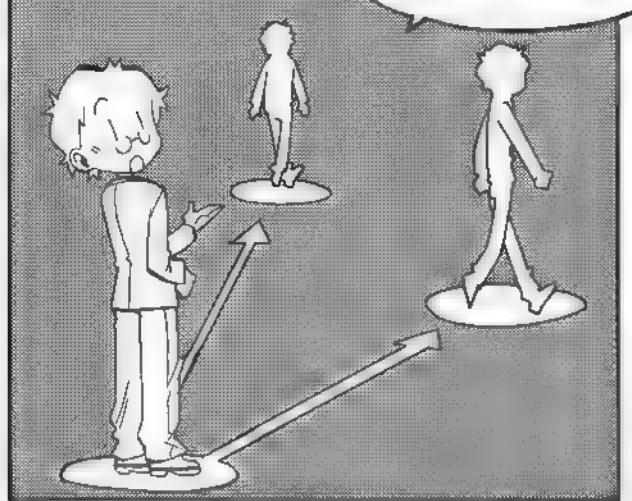
LET ME SEE...IS THAT SO-CALLED SIMPLE MOTION?

EXACTLY! YOU CAN OBTAIN THE SPEED OF SIMPLE MOTION AS FOLLOWS:

$$\text{SPEED} = \frac{\text{DISTANCE}}{\text{TIME}}$$

UH-HUH.  
THAT'S EASY.

HOWEVER, EVEN WHEN MY SPEED IS THE SAME, MY DESTINATION MAY BE DIFFERENT IF I MOVE IN A DIFFERENT DIRECTION.



SO, IN ORDER TO TAKE THE DIRECTION INTO ACCOUNT AS WELL, WE CAN REPLACE SPEED WITH VELOCITY AND DISTANCE WITH DISPLACEMENT IN OUR EARLIER EQUATION.



$$\text{VELOCITY} = \frac{\text{DISPLACEMENT}}{\text{TIME}}$$

SURE...WAIT!



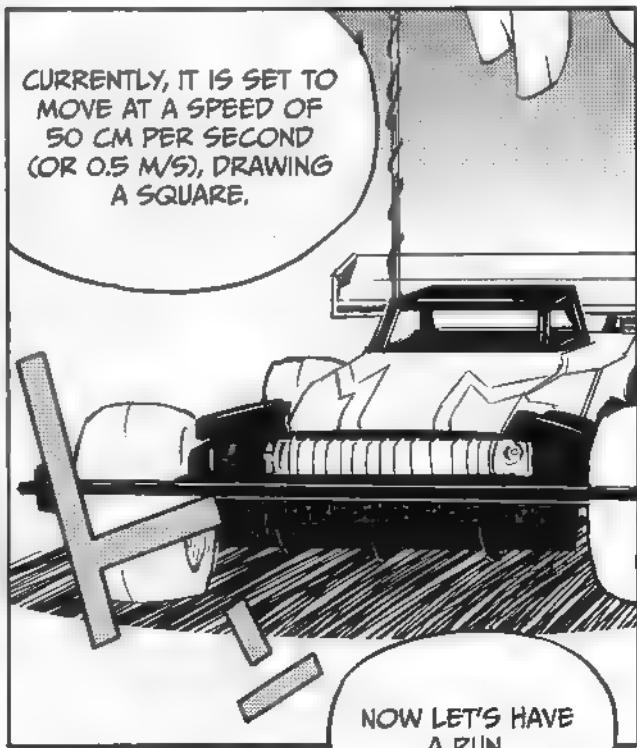
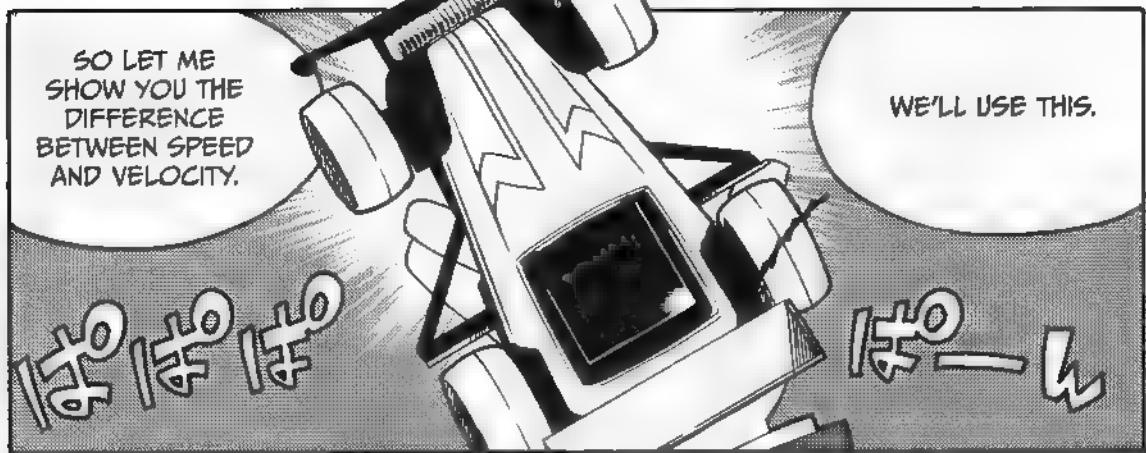
HOLD IT!

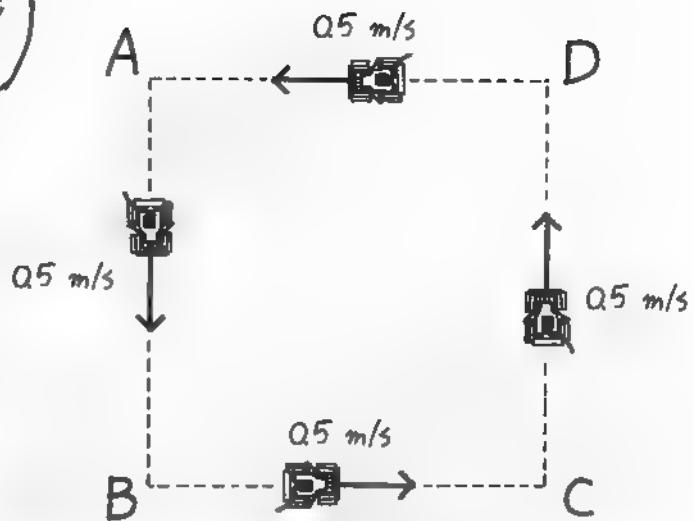
I HAVE A QUESTION!

ARE SPEED AND VELOCITY REALLY TWO DIFFERENT THINGS?

HEE-HEE!  
YOU'VE GOTTEN  
CAUGHT, IT SEEMS.







UNITS FOR SPEED: M/S  
(METERS PER SECOND)  
UNITS FOR DISTANCE: M (METERS)  
UNITS FOR TIME: S (SECONDS)

WHILE ITS SPEED  
IS CONSTANT,  
THE CAR MOVES  
IN DIFFERENT  
DIRECTIONS.

VELOCITY IS A VECTOR (IT HAS  
A DIRECTION AND MAGNITUDE),  
SO IT CAN BE EXPRESSED AS  
AN ARROW. SPEED IS JUST A  
MAGNITUDE.

THE LENGTH OF  
THE ARROW IS THE  
OBJECT'S MAGNITUDE  
(OR SPEED).

VELOCITY

THE ARROW POINTS IN  
THE DIRECTION OF THE  
VECTOR'S ORIENTATION.

WHEN TRAVELING ON SIDES  
AB AND CD IN THE DIAGRAM,  
THE CAR'S SPEED IS THE  
SAME, BUT ITS VELOCITY IS  
OPPOSITE. DO YOU SEE?

## ACCELERATION

LET'S CHANGE THE  
SETTING SO AS TO  
STEADILY INCREASE THE  
VELOCITY UP TO 0.5 M/S.

AN INCREASE IN VELOCITY  
IS CALLED ACCELERATION,  
WHICH YOU CAN CALCULATE  
USING THE EQUATION  
BELOW:

$$\text{ACCELERATION} = \frac{\text{CHANGE IN VELOCITY}}{\text{TIME}}$$

UH-HUH.

THE UNIT FOR  
ACCELERATION IS METERS  
PER SECOND SQUARED,  
WRITTEN AS  $\text{M/S}^2$ . IT  
REPRESENTS HOW THE  
VELOCITY (M/S) HAS  
INCREASED PER  
SECOND.

SO WE ARE  
DIVIDING THE  
CHANGE IN  
VELOCITY BY  
TIME.

YEP. IF VELOCITY  
STAYS THE SAME,  
THERE IS NO  
CHANGE, AND SO  
THE ACCELERATION  
IS ALSO ZERO.

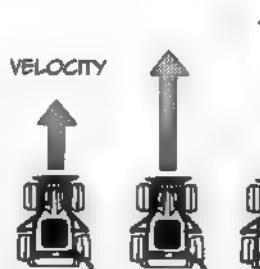
AS VELOCITY INCREASES,  
ACCELERATION HAS A  
POSITIVE VALUE. WHEN  
IT DROPS, OR THE  
MOTION SLOWS DOWN,  
ACCELERATION HAS A  
NEGATIVE VALUE.

YEP! YOU CAN CALL  
IT DECELERATION.

JUST THINK  
OF NEGATIVE  
ACCELERATION AS  
BEING EQUIVALENT  
TO A DECREASE IN  
VELOCITY.

ACCELERATION  
ALSO INVOLVES  
NEGATIVE VALUES?

MOTION WITH A CONSTANT  
INCREASE IN VELOCITY IS  
REFERRED TO AS UNIFORM  
ACCELERATION MOTION.

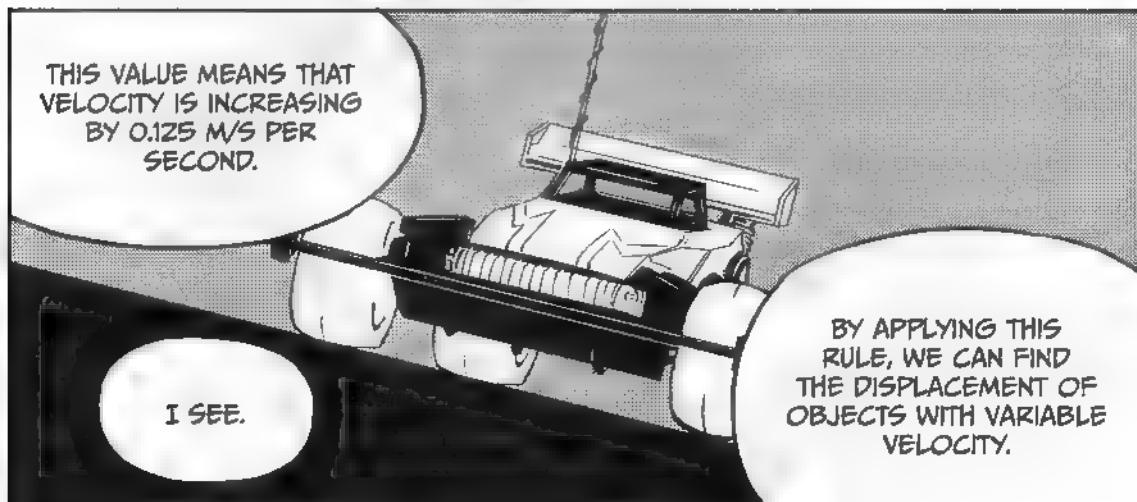
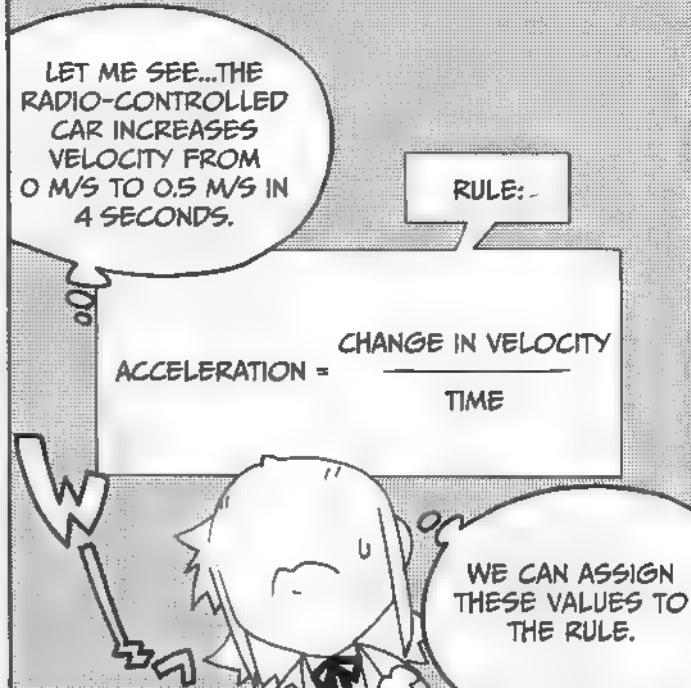
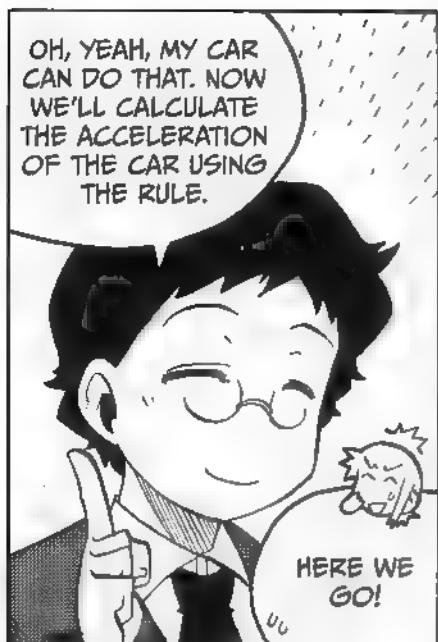


AND YOUR CAR CAN  
DO THAT WITH THE  
RIGHT PROGRAM?

WAIT...  
WE'RE THE  
TORTOISE  
AND THE  
HARE...?

SLOW AND STEADY  
WINS THE RACE!

HEY! HOW'D YOU  
GET SO FAR  
AHEAD?



# LABORATORY

## FINDING THE DISTANCE TRAVELED WHEN VELOCITY VARIES



Let's change the setting so as to steadily increase the velocity up to 0.5 m/s. Here's a quiz for you. Given that velocity has attained 0.5 m/s in four seconds, how far has the radio-controlled car moved?



Hmm . . . starting at 0 m/s, the peak velocity is 0.5 m/s. So let me calculate, assuming the average speed, 0.25 m/s, for the velocity.  $0.25 \text{ m/s} \times 4 \text{ s} = 1 \text{ m}$ !



That's right! You are so sharp. But can you explain why you can get the right answer with that calculation?



Uhm . . . remember, teaching me is *your* job, Nonomura-kun!



Ha ha, true enough. Before giving you a direct answer, let me explain how we can find the distance traveled when the velocity varies. When velocity is constant, we've learned that the distance traveled can be found by calculating the expression (speed  $\times$  time). Now, given that  $d$  m (meters) represents the distance traveled in  $t$  s (seconds) and the constant velocity is  $v$  m/s, then distance = speed  $\times$  time can be expressed in the following equation:

$$d = vt$$



Well, duh!





If you plot that relationship with velocity on the vertical axis and time on the horizontal axis, you get the following graph.



The shaded area represents the distance traveled. This chart is commonly referred to as a *v-t graph*, as it graphs velocity and time. That's the area of a rectangle having a horizontal length of  $t$  and a vertical length of  $v$ .



I see. It seems a little strange that an area represents a distance.

The area here is not a typical geometric area—this is a graph, like the ones you've seen in math class. The area of a geometric rectangle might be measured in square meters ( $\text{m}^2$ ). But in our example, the units are time (seconds) for the horizontal axis and velocity ( $\text{m/s}$ ) for the vertical axis. So the product of these two is equal to  $\text{s} \times \text{m/s} = \text{m}$ . That's our unit for distance.



It's easy to find distance when an object goes at a constant speed. But what about finding the distance when the speed is variable?



The only tool available to us is this equation:

$$\text{distance} = \text{speed} \times \text{time}$$



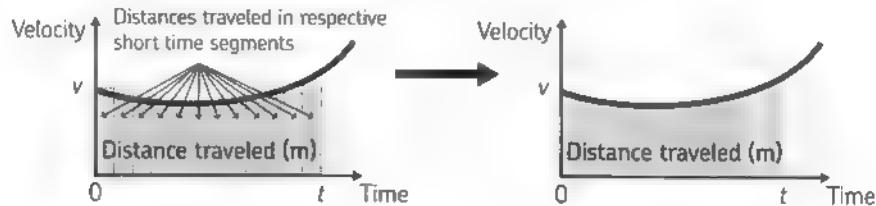
So we can divide the time into segments to create a lot of "small rectangles" and then calculate distances respectively, assuming a constant velocity for each time segment.



What do you mean?



Look at the chart on the left below.



So we can find the area of each slender rectangle created by dividing time into short segments, and then adding up the areas to find the distance traveled.



It bothers me that those little rectangles won't exactly fit the graph. Wouldn't they bring about errors?



I see your concern. Then we can sub-divide the rectangles into smaller segments. By repeating division into even smaller segments until everything fits as shown in the chart on the right above, the distance we get becomes more and more precise.



Well, I guess so . . . if you could do that . . .



If we divided them into infinitely slender rectangles, we'd find exactly how far the object has moved. After all, the ultimate answer we get by dividing distance = speed  $\times$  time into short time segments is the area created under a v-t graph. That's how we can find the distance traveled by finding the corresponding area. In summary,

$$\text{distance traveled} = \text{area under a v-t graph}$$

Just like that.\*

\* Students of calculus may notice that this process of finding an area under a graph is identical to *integration*.



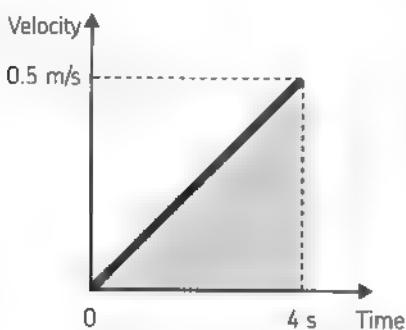
Now, keeping in mind what we've learned so far, let's examine the reason why the distance you got intuitively is the right answer.



All right!



Your original calculation is the same as calculating an area on a velocity-time graph. The example with a radio-controlled car can be plotted into a chart like this one.



The area under the graph, as obtained from the rule for the area of a triangle, is as follows:

$$\frac{1}{2} \times \text{base} (\text{time}) \times \text{height} (\text{max velocity}) = \frac{1}{2} \times 4 \text{ s} \times 0.5 \text{ m/s} = 1 \text{ m}$$

This represents the distance traveled.



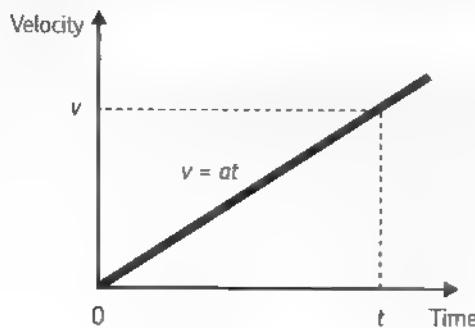
We got 1 meter for the answer, just as we should.



Let's find a general expression for the distance traveled, rather than using specific numeric values. Assuming velocity to be  $v$  and acceleration to be  $a$ , the relationship between the velocity and time for uniform accelerated motion is  $v = at$ .

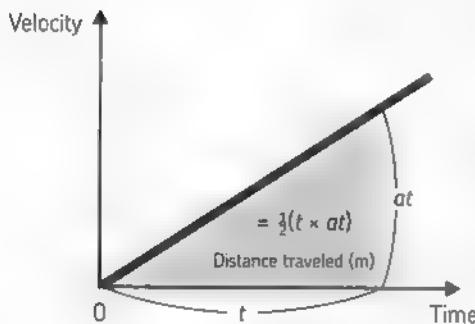


That can be plotted into a v-t graph, as shown below.



Let's assume  $d$  is the distance traveled in time  $t$ ; its value should be equivalent to the area of a triangle with a base of  $t$  and height of  $at$  (which equals the final velocity of the object).

$$d = \frac{1}{2}at^2$$



You see?

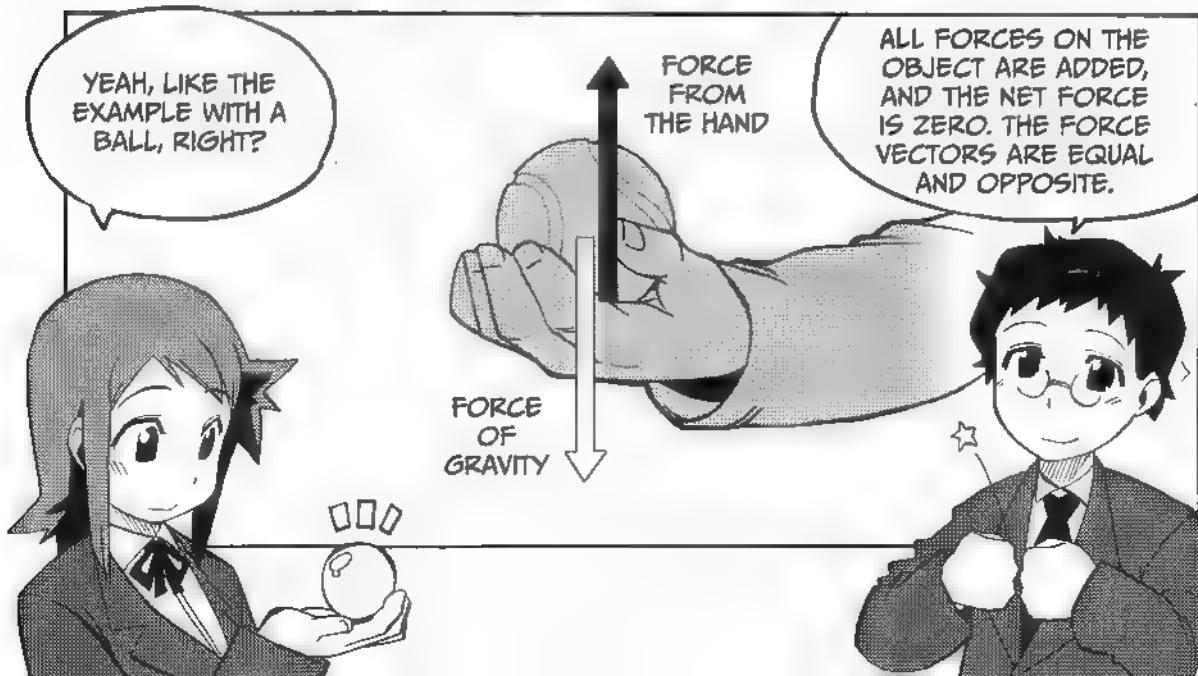
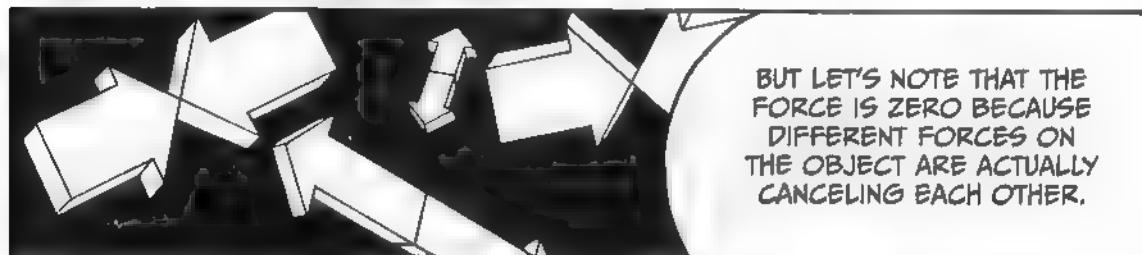
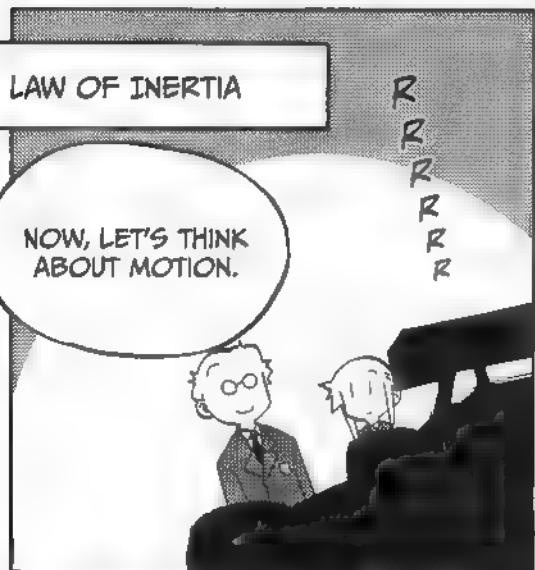


Ummmm . . . oh, I see how that works! The value we get by calculating  $\frac{1}{2} \times 0.125 \text{ m/s}^2 \times (4 \text{ s})^2 = 1 \text{ m}$ . As it should be!



Now, Ninomiya-san, you can also calculate a distance traveled in uniform accelerated motion not by intuition but by the proper method.

## NEWTON'S FIRST AND SECOND LAWS



SO AN OBJECT AT REST CAN HAVE FORCES IMPOSED ON IT, PROVIDED THAT THE SUM OF THOSE FORCES IS ZERO.

WHAT ON EARTH IS THIS?

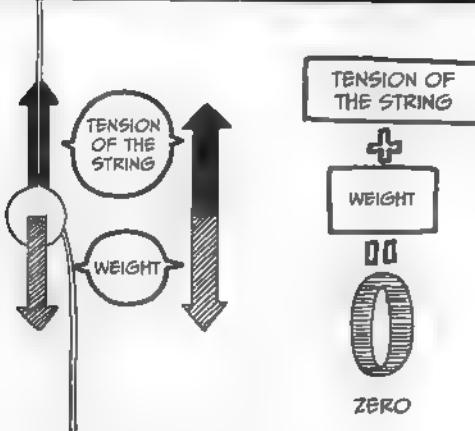
TO MAKE IT EASIER FOR YOU...

LOOK WHAT I HAVE PREPARED!

YOU DON'T HAVE TO BE APPALLED. IT'S JUST A BALL WITH TWO STRINGS COMING OUT OF IT.

SORRY.  
I'M A SPAZ.

CEILING



AT THE MOMENT, THE BALL IS STATIC.

SO A FORCE MUST BE IMPOSED FROM THE STRING THAT CAN CANCEL THE FORCE OF GRAVITY (THE BALL'S WEIGHT) TO YIELD A RESULT OF A ZERO MAGNITUDE.

YOU MEAN THE TENSION OF THE STRING IS EQUIVALENT TO THE FORCE OF GRAVITY?

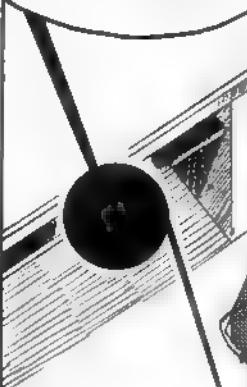
HOW CAN YOU SAY SO WITHOUT TAKING ANY MEASUREMENTS?

THAT'S MY POINT.

IN FACT, AN OBJECT AT REST, SUCH AS THIS BALL, IS RELATED TO NEWTON'S FIRST LAW OF MOTION.



YOU CAN CHECK THAT THE TENSION OF THE STRING IS EQUIVALENT TO THE BALL'S WEIGHT USING AN INSTRUMENT.



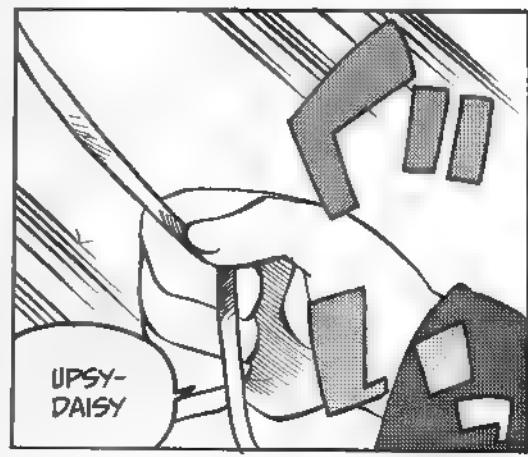
BUT THE FIRST LAW OF MOTION TELLS US THAT THE NET FORCE ON AN OBJECT IN A STATIC STATE MUST BE ZERO.

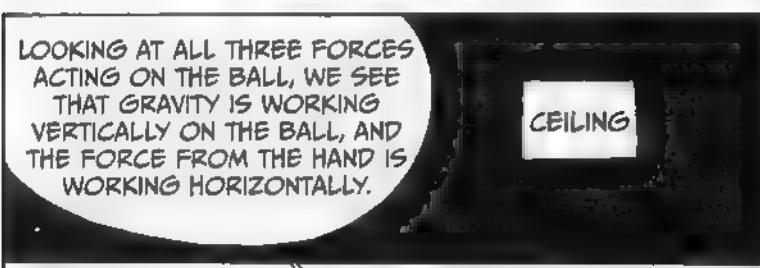


I SEE.

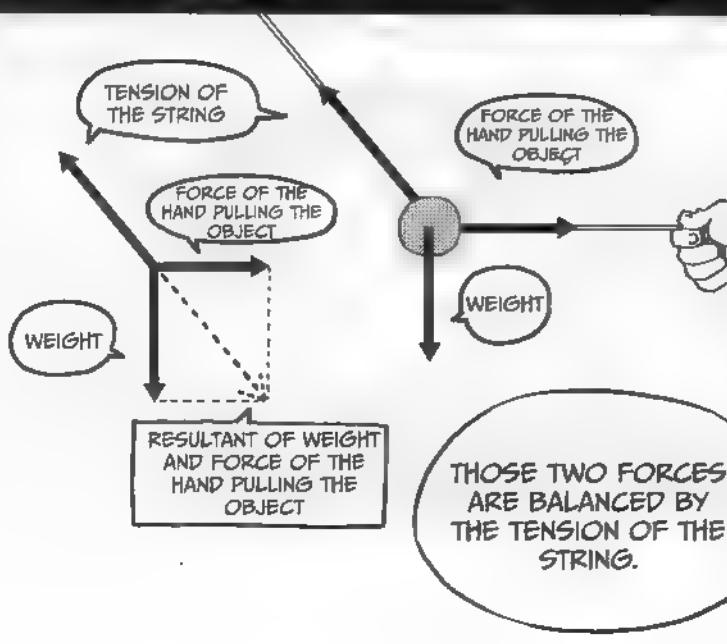
SO...I WONDER IF THE NET FORCE COULD BE ZERO IF THE OBJECT WAS PULLED BY THE SECOND STRING?

I THOUGHT I'D EXPLAIN IT...



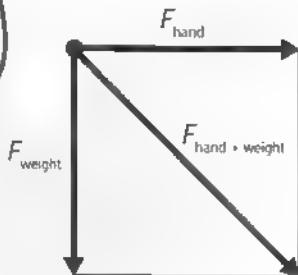


IN OTHER WORDS, THE BALL'S WEIGHT AND THE HAND'S FORCE CAN BE MERGED. OR CAN WE SPLIT THE TENSION OF THE STRING INTO TWO?

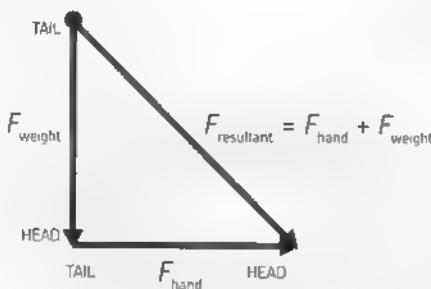




LET'S COMBINE TWO VECTORS INTO ONE. WE CAN ADD VECTORS BY SIMPLY PUTTING THE TAIL OF THE SECOND VECTOR ONTO THE HEAD OF THE FIRST. THIS IS CALLED THE HEAD-TO-TAIL METHOD.



DRAWING A FIGURE MAKES IT EASIER TO UNDERSTAND.

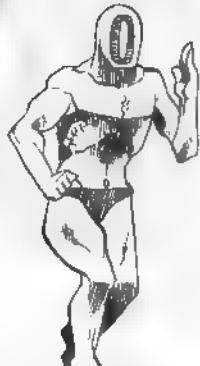


IN OUR EXAMPLE OF THE SUSPENDED WEIGHT, THE COMBINED FORCE OF MY HAND AND THE WEIGHT HAS AN EQUIVALENT MAGNITUDE (IN THE EXACT OPPOSITE DIRECTION) TO THE TENSION OF THE STRING. WE KNOW THAT THE OBJECT IS AT REST, SO THE TOTAL RESULTANT FORCE MUST EQUAL ZERO.



IF, WHEN FORCES ARE IMPOSED, THE OBJECT REMAINS STATIONARY,

THE SUM OF THE FORCES IS ZERO.



RIGHT...

BUT IT'S POSSIBLE FOR AN OBJECT TO BE IN MOTION EVEN WHEN FORCES ARE ZERO.



NO WAY!

FOR EXAMPLE, THINK OF OUTER SPACE.

POW  
POW

OUTER SPACE?

HAVEN'T YOU SEEN FOOTAGE OF THE INTERIOR OF A SPACE SHUTTLE?

SURE I HAVE! THERE ARE ALWAYS VARIOUS THINGS SUSPENDED IN THE AIR.

IN A SO-CALLED WEIGHTLESS STATE, AN OBJECT THAT HAS STARTED MOVING TRAVELS STRAIGHT AHEAD AT A CONSTANT RELATIVE VELOCITY.\*



IT LOOKS LIKE YOU MAY BE RIGHT.

\* IN ORBIT, OBJECTS ARE IN A STATE OF CONSTANT FREE FALL, MAKING THEIR APPARENT WEIGHT ZERO.

NORMALLY, FRICTION FROM THE AIR OR COLLISION WITH THE GROUND WILL STOP AN OBJECT (UNLESS YOU KEEP APPLYING A FORCE).

WHOOPEE!

BUT IN DEEP OUTER SPACE, IT IS POSSIBLE TO ACHIEVE A ZERO-FORCE STATE, AS THERE IS NO GRAVITY OR AIR RESISTANCE TO CONSIDER.

YES, INDEED! IN THAT CASE, YOU MEAN, WE COULD KEEP MOVING FOREVER, EVEN WITH NO FORCE IMPOSED?

EXACTLY!

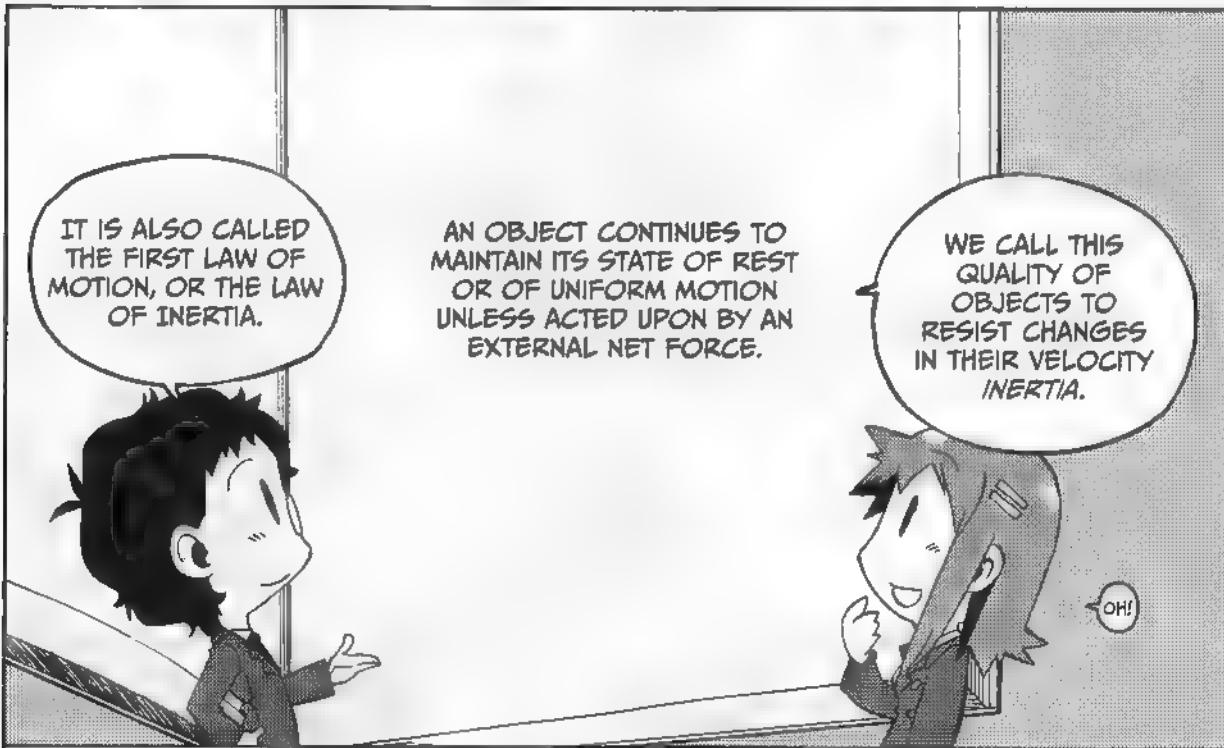
IS THAT GUY ALL RIGHT?

A CONSTANT-VELOCITY, OR UNIFORM, MOTION OCCURS WHEN THE NET FORCE IS ZERO.

HE LOOKS LIKE HE'S LEAVING.

WELL...

HISS



## LAW OF ACCELERATION

NEXT, LET'S EXAMINE THE MOTION OF AN OBJECT WHEN A NET FORCE IS WORKING.

YOU COMMUTE BY BICYCLE, DON'T YOU, NINOMIYA-SAN?

HEY, IT'S MEGU!

HI GUYS!

YES, I DO. THOUGH IT'S A RATHER LONG WAY FROM HOME.

OF COURSE, YOU INTUITIVELY KNOW THAT A BICYCLE AT REST MUST BE PEDALED TO START MOVING.

IN OTHER WORDS, YOU CAN SAY THAT ITS VELOCITY HAS CHANGED.

YOU COULD SAY THAT THE APPLICATION OF FORCE (FROM YOUR LEGS) HAS GENERATED ACCELERATION.

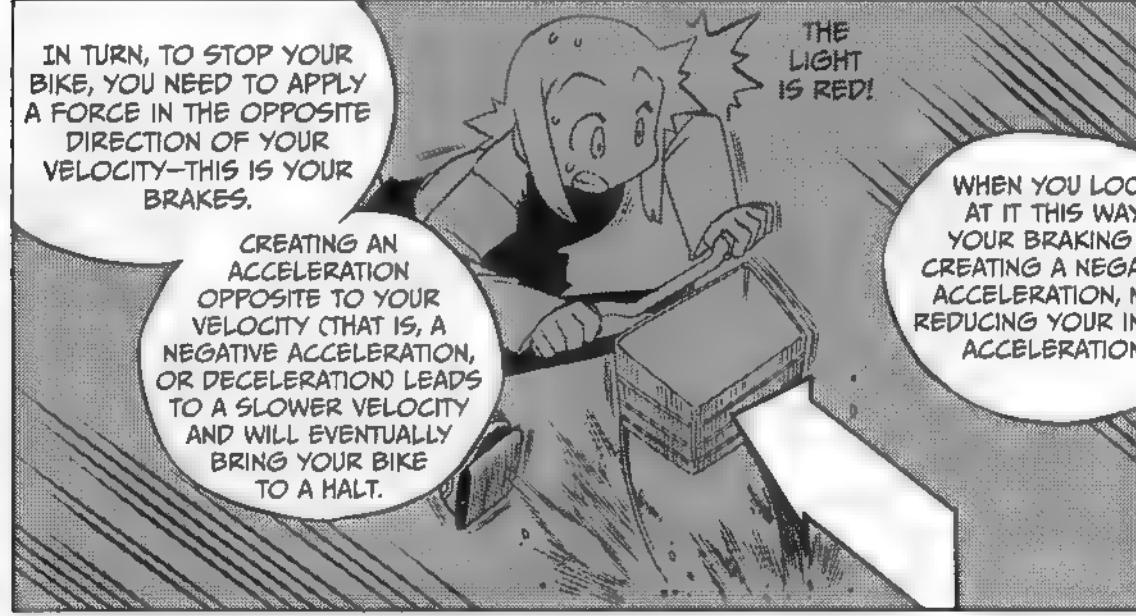
OH-HUH.



AND THE GREATER  
THE FORCE IS,  
THE GREATER THE  
ACCELERATION  
BECOMES.

HAVE TO  
HURRY! I'M  
RUNNING  
LATE...

MY INTUITION  
TELLS ME THAT.



IN TURN, TO STOP YOUR  
BIKE, YOU NEED TO APPLY  
A FORCE IN THE OPPOSITE  
DIRECTION OF YOUR  
VELOCITY—THIS IS YOUR  
BRAKES.

CREATING AN  
ACCELERATION  
OPPOSITE TO YOUR  
VELOCITY (THAT IS, A  
NEGATIVE ACCELERATION,  
OR DECELERATION) LEADS  
TO A SLOWER VELOCITY  
AND WILL EVENTUALLY  
BRING YOUR BIKE  
TO A HALT.

THE  
LIGHT  
IS RED!

WHEN YOU LOOK  
AT IT THIS WAY,  
YOUR BRAKING IS  
CREATING A NEGATIVE  
ACCELERATION, NOT  
REDUCING YOUR INITIAL  
ACCELERATION.



GIVEN THESE  
OBSERVATIONS, WE  
CAN SAFELY SAY THAT  
THE FORCE IS DIRECTLY  
PROPORTIONAL TO THE  
ACCELERATION.

OKAY...

NOW, LET'S FOCUS ON MASS.

THAT'S HUGE! AND HEAVY!

WITH A HEAVY LOAD IN YOUR BASKET, YOU MUST EXERCISE A HUGE FORCE WHEN YOU INITIALLY TRY TO PUSH THE PEDAL.

OH  
OH  
OH

CREEEAK



SEE, THE LOAD MAKES IT HARDER TO ACCELERATE.

GIVEN THAT, WE CAN ASSUME THAT THE MASS IS INVERSELY PROPORTIONAL TO ACCELERATION.

PUFF  
PUFF  
PUFF  
WHEEZE

THAT MEANS THE LARGER THE MASS, THE SMALLER THE ACCELERATION.

WAIT, WHAT'S THE DIFFERENCE BETWEEN WEIGHT AND MASS?

TO PUT IT SIMPLY, WEIGHT IS A FORCE IMPOSED ON AN OBJECT BY GRAVITY.

THIS MEANS AN OBJECT WILL HAVE A DIFFERENT WEIGHT ON THE MOON THAN ON EARTH.

SO WHAT ABOUT MASS?



IN DEEP OUTER  
SPACE, AN  
OBJECT WEIGHS  
NOTHING.

HOWEVER, TO  
MOVE IT, YOU  
STILL NEED A  
FORCE.

OF  
COURSE!

MASS IS A QUANTITY THAT DETERMINES AN OBJECT'S INERTIA, OR RESISTANCE TO ACCELERATION—IT'S AN INHERENT QUALITY OF AN OBJECT THAT DOES NOT DEPEND ON GRAVITATIONAL PULL.

WEIGHT AND MASS  
SEEM SIMILAR,  
BUT THEY MEAN  
DIFFERENT THINGS,  
DON'T THEY?

LET'S SUM UP  
WHAT WE'VE  
LEARNED  
SO FAR!

UH, OKAY.

THE ACCELERATION OF AN OBJECT IS PROPORTIONAL TO THE FORCE APPLIED TO IT AND INVERSELY PROPORTIONAL TO ITS MASS.

THIS IS THE  
SECOND LAW OF  
MOTION.

HAS IT CAUGHT YOUR FANCY  
BY ANY CHANCE? JUDGING  
FROM YOUR POSE...

OH, YES.

OH-H-H!  
I SEE.

NOW LET'S  
EXPRESS IT IN AN  
EQUATION.

ASSUME ACCELERATION IS  
 $a$  (IN  $M/S^2$ ). FORCE IS  $F$  (IN  
NEWTONS, A UNIT EQUAL TO  
[ $KG \times M$ ] /  $S^2$ ). MASS IS  $m$   
ON  $KG$ ). THEN,



OH NO, AN  
EQUATION?

WE GET THE  
FOLLOWING.

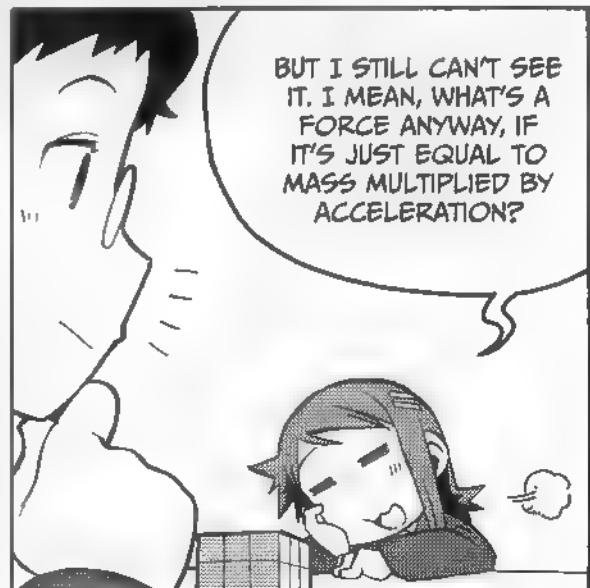
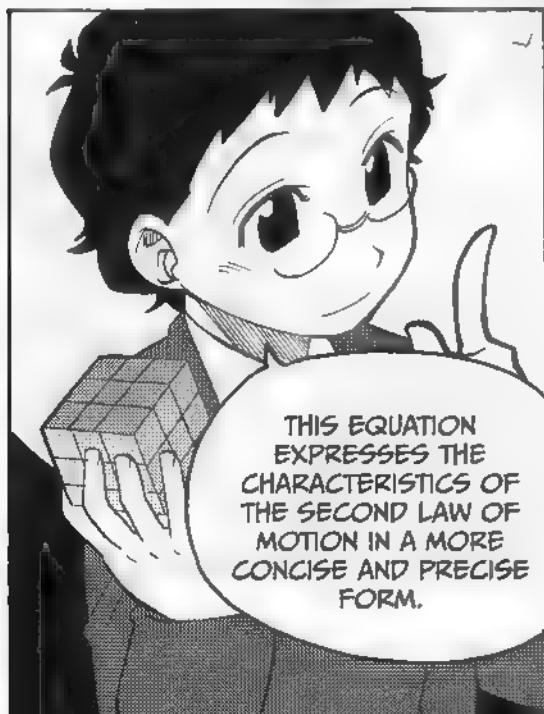
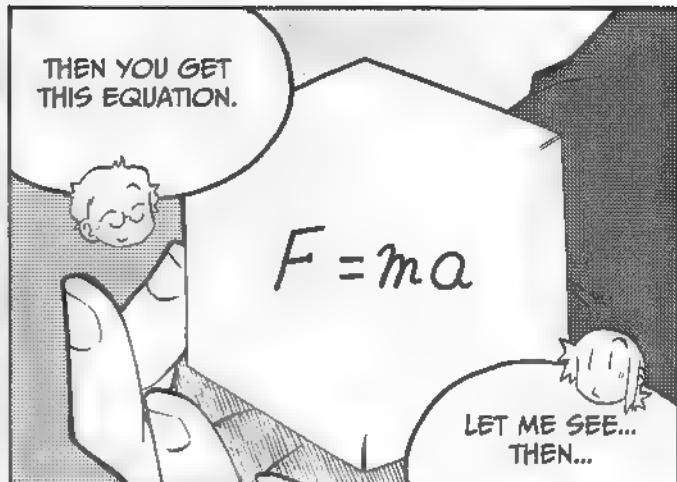
THE EQUATION SHOWS  
THIS: WHEN FORCE  $F$  IS  
DOUBLED, ACCELERATION  $a$   
IS ALSO DOUBLED. YOU SEE,  
WHEN MASS  $m$  IS DOUBLED,  
ACCELERATION  $a$  IS REDUCED  
TO HALF.

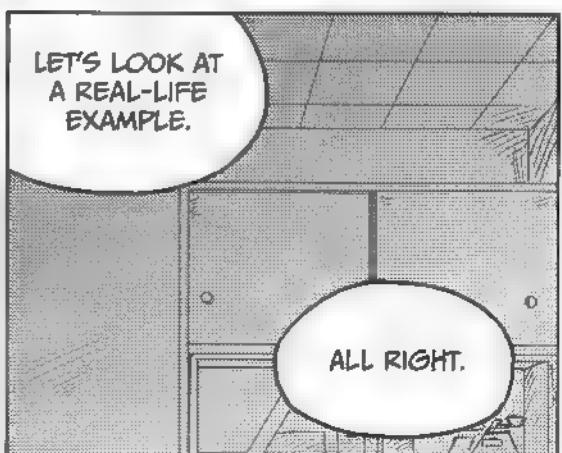
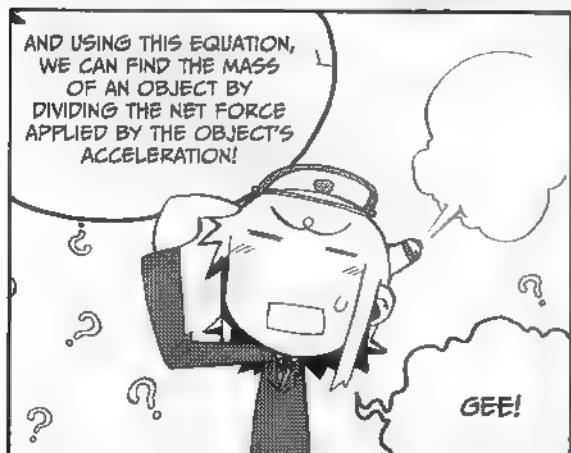
$$2^a = \frac{2^F}{1^m}$$



$$\frac{1^a}{2} = \frac{1^F}{2^m}$$

NOTHING LIKE AN  
EQUATION TO RUIN  
YOUR DAY.





# LABORATORY

## FINDING THE PRECISE VALUE OF A FORCE



Earlier, we pushed each other while we were on roller blades. Let's say that I captured our motion on video.



I didn't realize you were taping us!



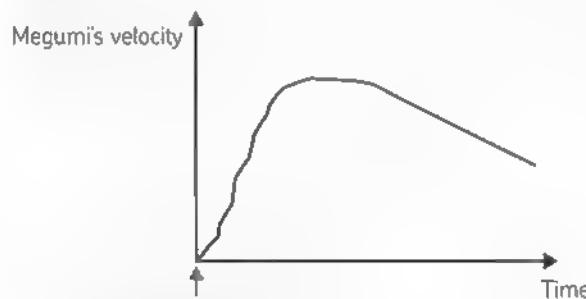
Oh, that's just the scenario I'm setting up.



Jeez, don't scare me. How does that relate to the second law of motion?



Suppose I have analyzed the video, and I've created a v-t graph of your motion.

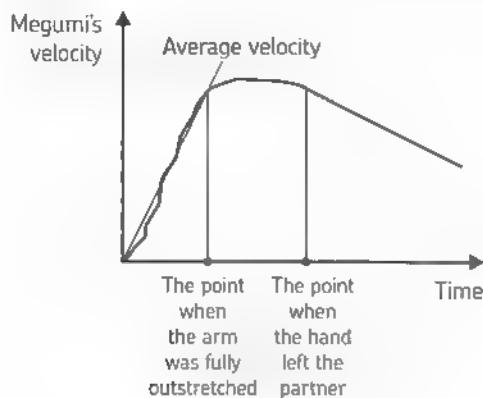


We can see that velocity increases sharply from zero, which must be when I'm at rest, and then drops gradually after that. But the initial increase in velocity is wobbly.





In a case like this, it may be a good idea to draw a line segment that represents the average increase in velocity. In other words, we'll simplify the scenario to assume this is a case of uniform acceleration.



I see.



You can find acceleration by calculating the change in velocity over time—acceleration = change in velocity / time. In this case, let's assume that your acceleration is equal to  $0.6 \text{ m/s}^2$ . To find the force I applied to your hands, let's also assume your mass is 40 kg. Ninomiya-san.

$$F = ma = 40 \text{ kg} \times 0.6 \text{ m/s}^2 = 24 \text{ kg} \times \text{m/s}^2, \text{ or } 24\text{N}$$



We've found the precise value of the force! So, this is important! We can measure the exact force on an object by measuring its acceleration and its mass.



Now, if you know that I weigh 60 kg, can you predict my acceleration, due to the application of an equal and opposite 24N of force?



Oh, I see. We're combining the second and third laws of motion.  $F_{\text{Megumi}}$  must equal  $F_{\text{Ryota}}$ . Since  $F = ma$ , we know that  $F / m = a$ . In your case, that's  $24\text{N} / 60 \text{ kg}$ , or  $0.4 \text{ m/s}^2$ . So we can use these laws to predict the movement of objects. Neat!

## MOTION OF A THROWN BALL



FIRST, LET'S THINK ABOUT AN OBJECT MOVING IN A PARTICULAR DIRECTION.

WON'T THE FORCE ON THE OBJECT BE IN THE SAME DIRECTION AS ITS MOTION?

YES, A BALL MOVES IN THE SAME DIRECTION AS THE INITIAL FORCE THAT WAS IMPOSED ON IT.

IMAGINE I THROW THIS BALL IN THE AIR. SUPPOSE THE BALL IS AT POINT A, B, OR C. DRAW THE ORIENTATION OF THE FORCE IMPOSED ON THE BALL.

LET'S IGNORE AIR RESISTANCE.

THE ORIENTATION OF THE THROWING FORCE

A

THE POSITION 0.2 SECONDS AFTER LEAVING THE HAND

B

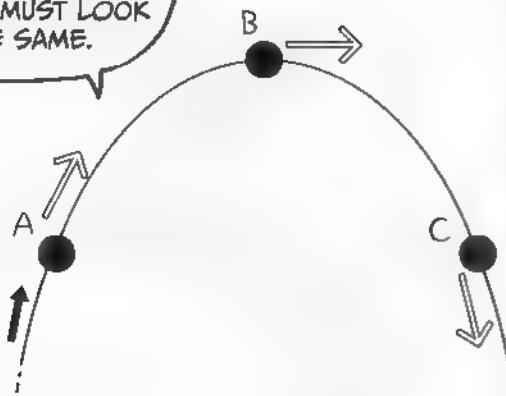
THE POSITION AFTER 0.4 SECONDS

C

THE POSITION AFTER 0.6 SECONDS



WELL, SINCE THE  
BALL'S VELOCITY  
LOOKS LIKE THIS, THE  
FORCE MUST LOOK  
THE SAME.



OH, NO, YOU  
HAVE BEEN  
TRICKED BY MY  
QUESTION.



WHY ARE  
YOU ALWAYS  
TRICKING ME?!

IN YOUR  
DIAGRAM ABOVE,  
WHERE IS THE  
FORCE OF  
GRAVITY ON THE  
BALL?

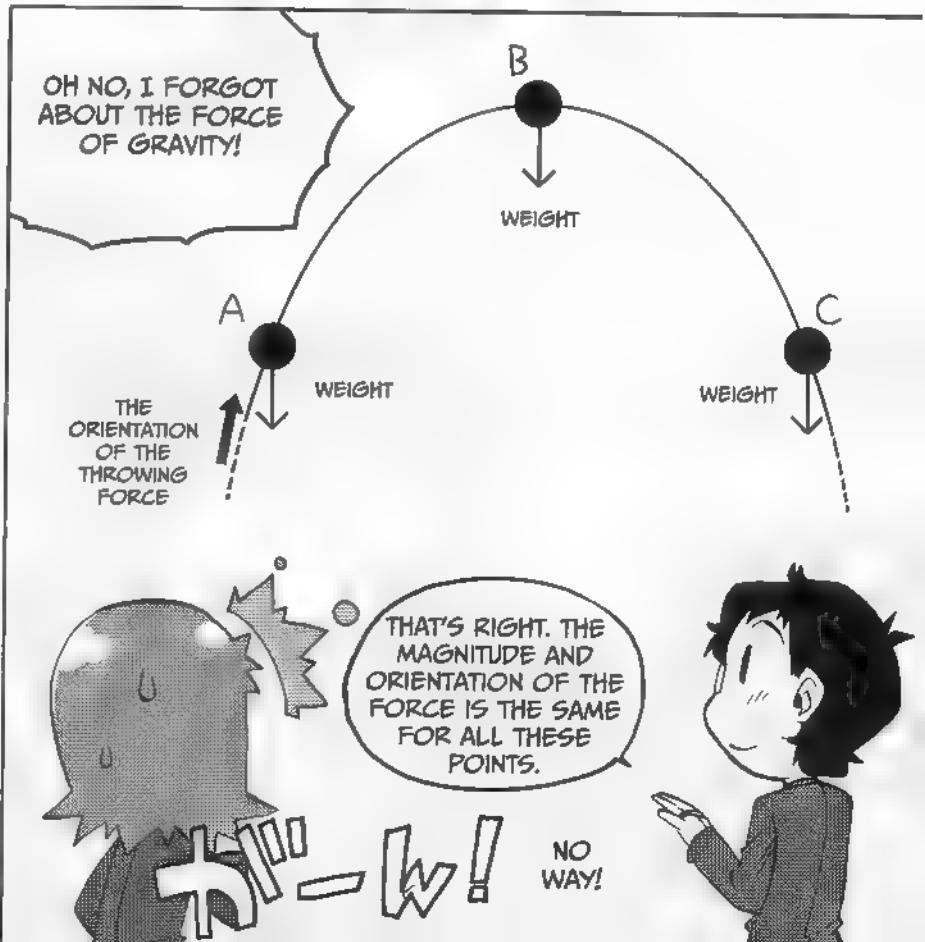


LET ME SEE...I GUESS I  
THOUGHT I DREW THE  
RESULT OF ALL FORCES,  
INCLUDING GRAVITY. BUT  
NOW I'M NOT SO SURE.

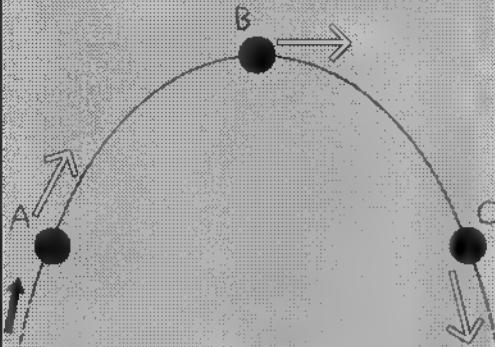
AT POINT A, YOU DREW  
A FORCE WORKING ON  
THE BALL, DIAGONALLY  
UPWARD. WHERE DOES  
THAT FORCE COME  
FROM?



WELL...IT'S THE  
FORCE OF YOUR  
HAND BEING  
IMPOSED ON THE  
BALL, RIGHT?



BUT DOESN'T THE  
BALL FORM A  
PARABOLA AS IT  
MOVES THROUGH  
THE AIR?



YES, BUT THAT'S  
BECAUSE THE  
ORIENTATION OF THE  
VELOCITY CHANGES,  
NOT THE FORCE.

INDEED, THE CHART  
YOU'VE DRAWN INDICATES  
THE ORIENTATION OF  
THE VELOCITY, NOT THE  
FORCE.

THE ORIENTATION  
OF THE VELOCITY,  
YOU SAY...

DON'T THINK OF  
VELOCITY AS  
CORRESPONDING  
TO THE ORIENTATION  
OF THE FORCE.

FOR EXAMPLE, THE  
FORCE STOPPING AN  
OBJECT WORKS IN THE  
OPPOSITE DIRECTION  
OF ITS VELOCITY,  
RIGHT?

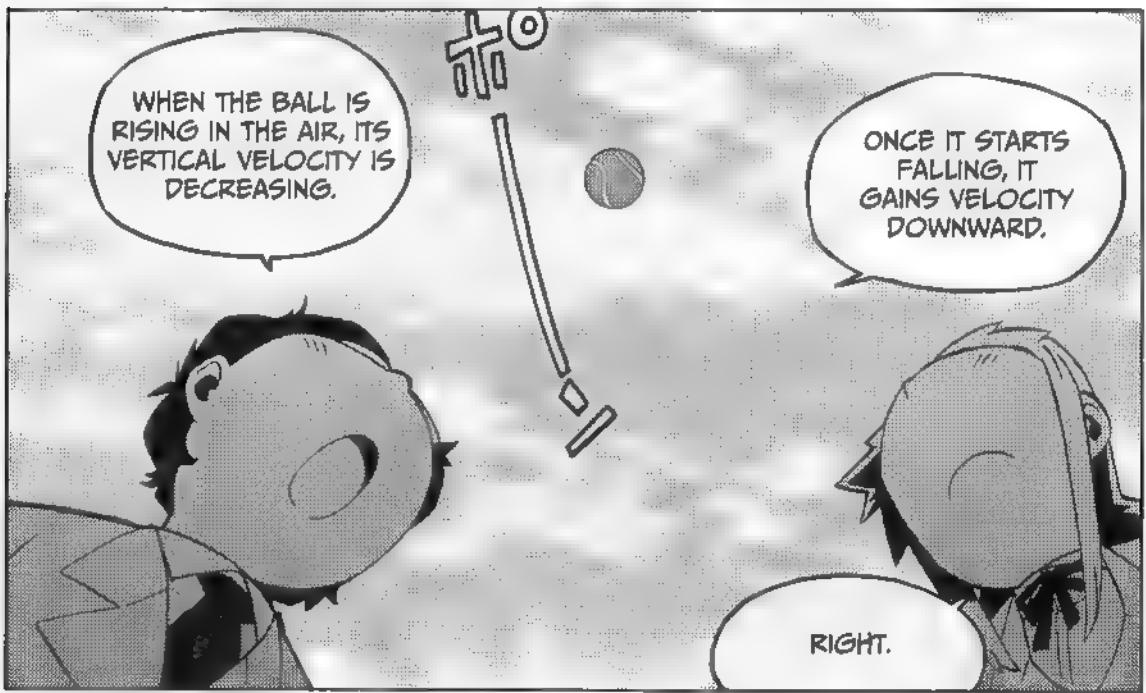
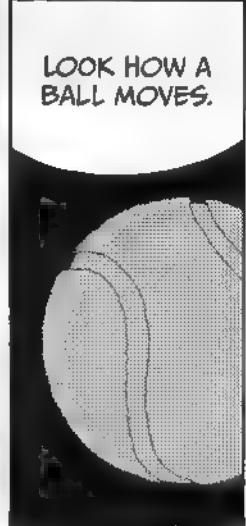
YES, INDEED,  
THAT'S TRUE.

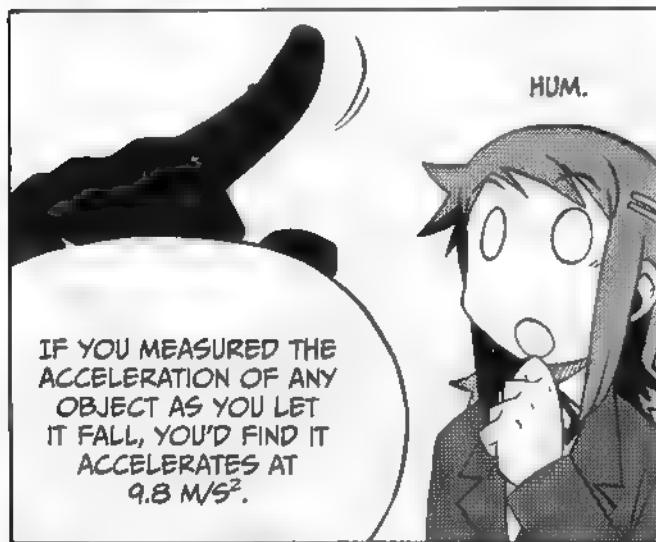
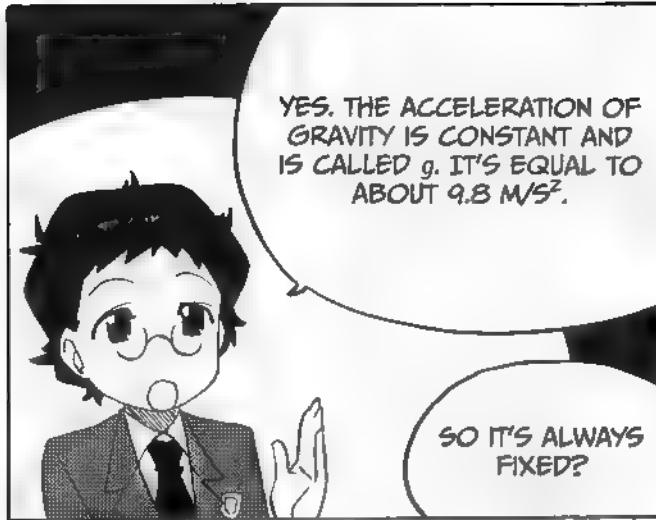
THE ORIENTATION OF THE  
VELOCITY OF AN OBJECT  
DOES NOT NEED TO MATCH  
THE ORIENTATION OF THE  
FORCE IMPOSED ON IT.

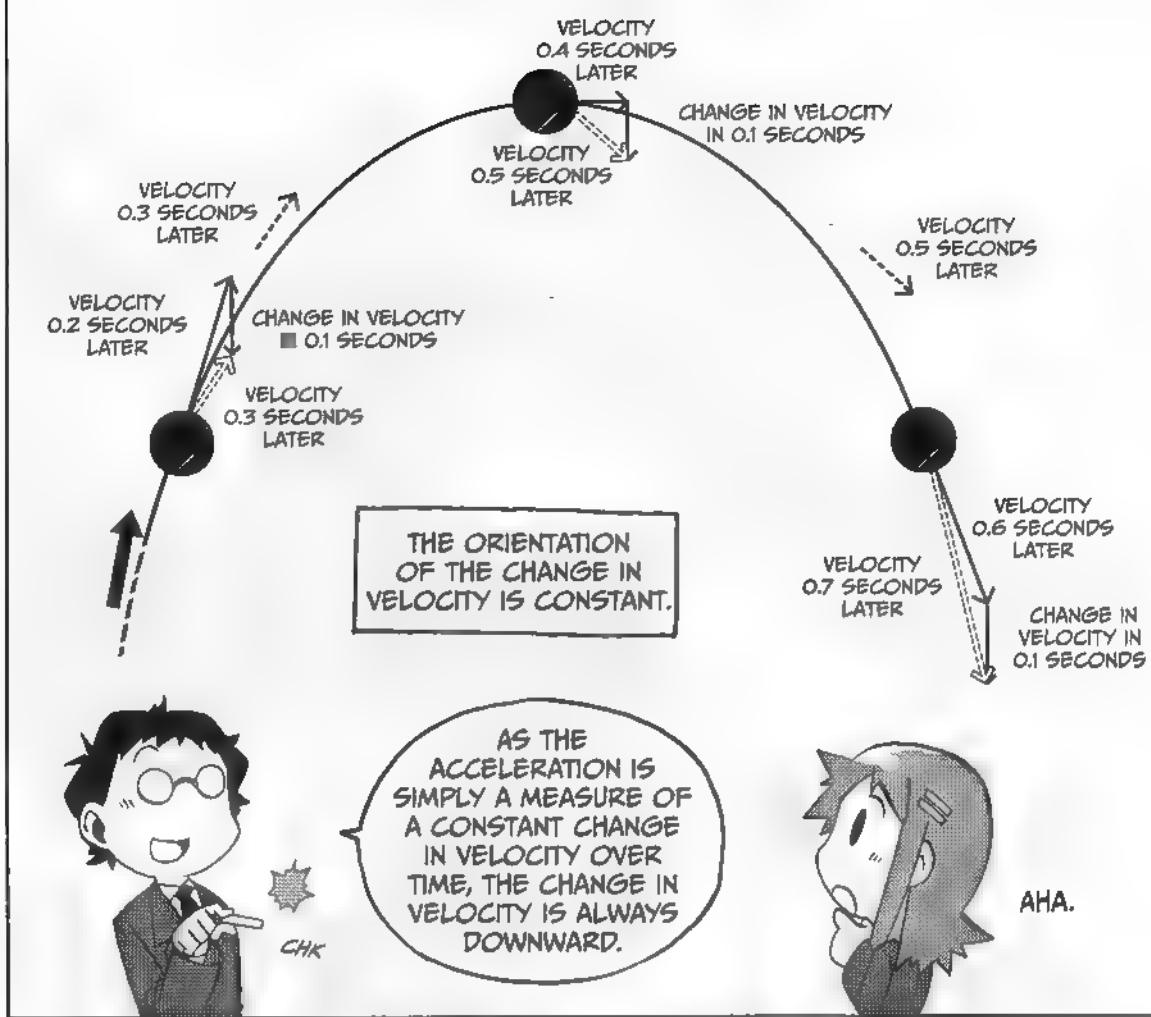
HOWEVER,

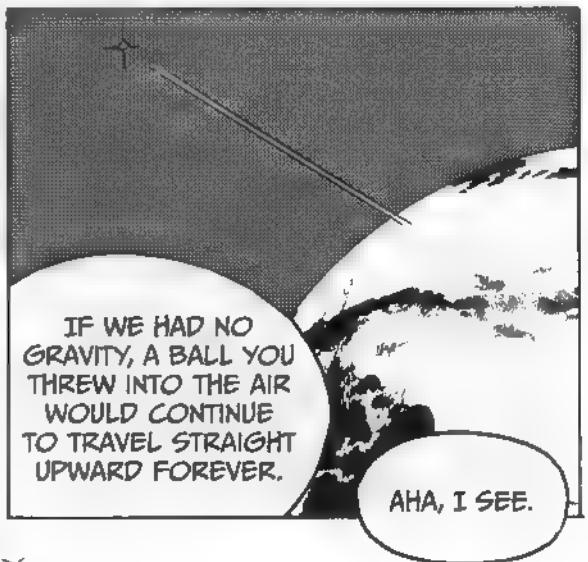
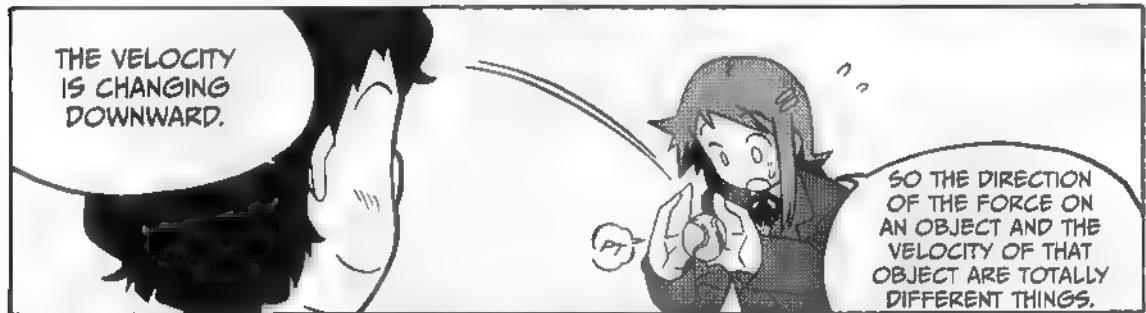
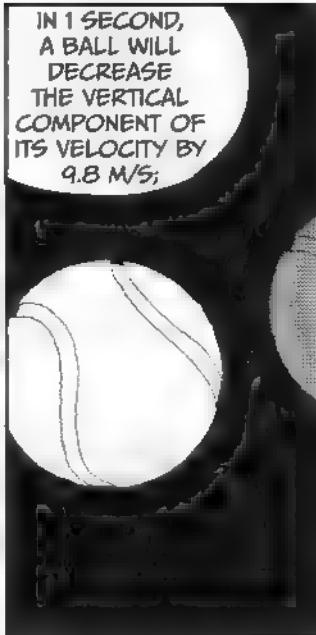
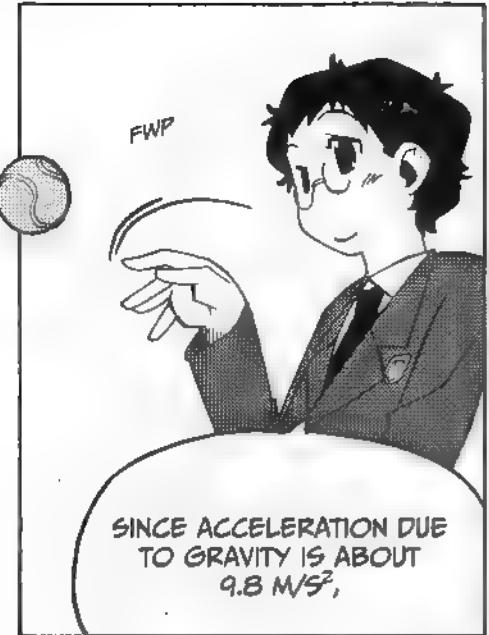
THE ORIENTATION OF  
THE FORCE ALWAYS  
MATCHES THAT OF THE  
ACCELERATION.













THE PHYSICS OF MOTION IS MADE OF THREE LAWS—THE ONES WE'VE LEARNED. NO EXAGGERATION!

WOW, REALLY? THEY MUST BE PRETTY GREAT LAWS!

NEXT, WE'RE GOING TO LEARN ABOUT MOMENTUM.

LET'S KEEP UP THE PACE!

ALL RIGHT! HA, HA.

WE STAYED SO LATE AGAIN!

WHY ARE THEY ALWAYS STUDYING TOGETHER IN THE PHYSICS LAB?

...THOSE TWO...

SUSPICIOUS...

## THREE RULES OF UNIFORM ACCELERATED MOTION



Let's look at the uniform accelerated motion of an object traveling in a straight line. Assuming the initial velocity of the object is  $v_1$ , the velocity after time  $t$  is  $v_2$ , the distance traveled in time  $t$  is  $d$ , and the uniform acceleration of the object is  $a$ , the following three rules are true:

- $v_2 = at + v_1$
- $d = v_1 t + \frac{1}{2} a t^2$
- $v_2^2 - v_1^2 = 2ad$

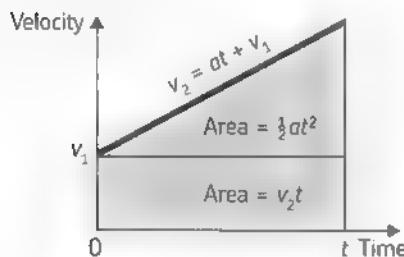
Let's derive these rules. First, let's look at rule ●. If the acceleration is constant, the following is true:

$$\text{change in velocity} = \text{acceleration} \times \text{time}$$

Since the change in velocity is equal to  $v_2 - v_1$ , acceleration is  $a$ , and time is  $t$ , we can derive the following equation to get rule ●:

$$v_2 = at + v_1$$

Next, let's derive rule ●. On page 54, we learned that the distance an object travels can be expressed as the area under a v-t graph. According to rule ●, the v-t graph should look like the following figure.



The area of this v-t graph is equal to the distance the object travels.

Since the area of the rectangular portion in the lower section of the v-t graph is  $v_1 t$ , and the area of the triangular portion above is  $\frac{1}{2}at^2$ , we get the following equation:

$$d = v_1 t + \frac{1}{2} a t^2$$

**NOTE** Technically,  $d$  represents displacement and not distance.

Rule ❶ can be derived by removing  $t$  from rules ❷ and ❸. First, let's solve equation ❶ for  $t$ :

$$\frac{(v_2 - v_1)}{a} = t$$

If we substitute this value into rule ❷, the following equation will be the result:

$$d = v_1 \left( \frac{v_2 - v_1}{a} \right) + \frac{1}{2} a \left( \frac{v_2 - v_1}{a} \right)^2$$

$$d = \frac{v_1 v_2 - v_1^2}{a} + \frac{1}{2} a \left( \frac{v_2^2 - 2v_1 v_2 + v_1^2}{a^2} \right)$$

$$d = \frac{2v_1 v_2 - 2v_1^2 + v_2^2 - 2v_1 v_2 + v_1^2}{2a}$$

$$d = \frac{v_2^2 - v_1^2}{2a}$$

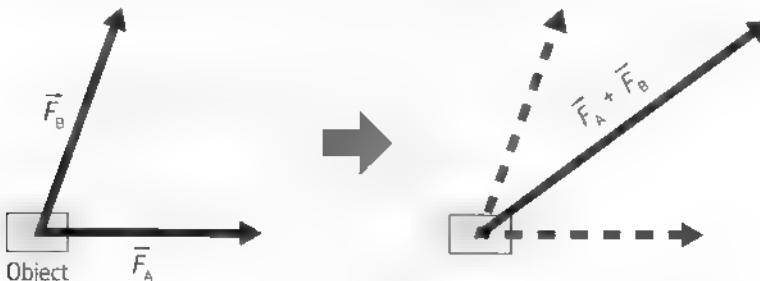
Voilà! Simply multiply both sides by  $2a$ , and you've just derived rule ❶!

## ADDING VECTORS: THE HEAD-TO-TAIL METHOD

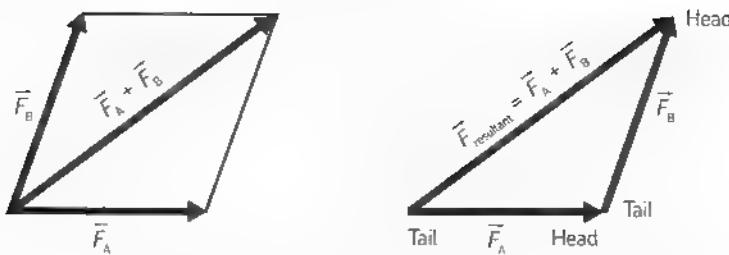


Because force is a vector, we need to make calculations according to the rules of vectors I explained in Chapter 1. If two vectors are parallel, adding them is simple—you can either add their magnitudes or subtract one from the other (if the two vectors are in opposite directions).

However, in the real world, we'll have to add vectors pointing in all different directions. To do this, we'll use the head-to-tail method. To illustrate, let's assume that an object is receiving two forces,  $\vec{F}_A$  and  $\vec{F}_B$ , as seen below.



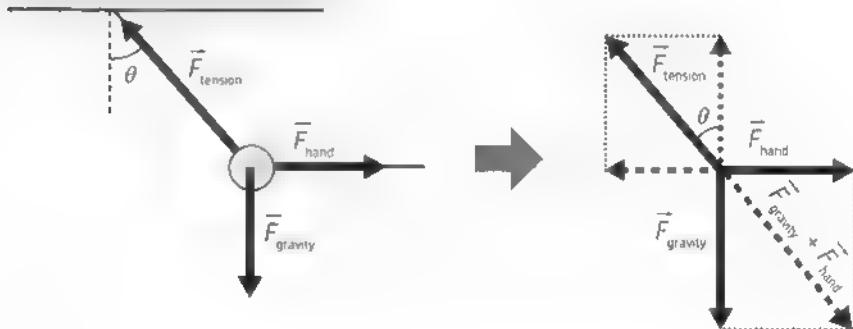
The total force on the object is equal to one combined force, represented by the arrow shown on the right. This arrow is the sum of the forces  $\vec{F}_A + \vec{F}_B$ , and we'll call it  $\vec{F}_{\text{resultant}}$ . But how can we find its exact magnitude and direction?



To determine the magnitude and the direction of a resultant force, you can simply place the head of one vector onto the tail of the second. The resultant force connects from the tail of the first vector to the head of the second. The resultant vector  $\vec{F}_{\text{resultant}}$  forms a triangle with  $\vec{F}_A$  and  $\vec{F}_B$ , as you can see on the right. You can use the head-to-tail method for any vector, not just forces, and you can find the resultant force from three or more forces by repeatedly applying the head-to-tail method.

## THE COMPOSITION AND DECOMPOSITION OF FORCES

To make forces easier to understand and analyze, we'll often split them into their horizontal and vertical constituent parts. That's because the head-to-tail method also works in reverse. That is, we can split a single diagonal force into the addition of its horizontal and vertical parts. Let's look at an example.



Let's look at the balance of forces when a weight hanging from the ceiling is pulled horizontally (see page 61). As shown on the right in the figure above, let's assume gravity is  $\vec{F}_{\text{gravity}}$ , the force from the hand pulling horizontally is  $\vec{F}_{\text{hand}}$ , and the tension of the string is  $\vec{F}_{\text{tension}}$ . When the weight is stationary, the three forces are balanced. Thus, adding the three forces as vectors yields zero:

$$\vec{F}_{\text{gravity}} + \vec{F}_{\text{hand}} + \vec{F}_{\text{tension}} = 0$$

You can rewrite this equation as the following:

$$\vec{F}_{\text{gravity}} + \vec{F}_{\text{hand}} = -\vec{F}_{\text{tension}}$$

With this in mind, let's revisit our diagram, thinking in terms of horizontal and vertical forces. Because the object is at rest, forces in the horizontal direction must equal zero. In the same way, the sum of the forces in the vertical direction must equal zero.

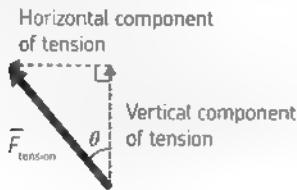
What are the horizontal forces in play?  $F_{\text{hand}}$  and the horizontal component of the tension of the string,  $F_{\text{tension}}$ . They are acting in opposite directions, and the object is at rest, so these two forces must be equal:

$$F_{\text{hand}} = \text{horizontal component of } F_{\text{tension}}$$

What are the vertical forces acting on the object? The force of gravity downward and the vertical portion of the tension of the string,  $F_{\text{tension}}$ . They are acting in opposite directions, and the object is at rest, so these forces must also be equal:

$$F_{\text{gravity}} = \text{vertical component of } F_{\text{tension}}$$

So, how can we actually "decompose" the force of the tension into its horizontal and vertical parts? We'll use concepts from *trigonometry*, the study of triangles.



Remember the head-to-tail method of addition of vectors? Here we'll decompose our diagonal force,  $F_{\text{tension}}$ , into its horizontal and vertical parts, forming a right triangle. If the angle of this triangle is represented by  $\theta$ , we can represent the horizontal and vertical constituent parts in terms of this angle! Recalling the previous two equations, we get the following:

$$\textcircled{1} \quad F_{\text{hand}} = \sin \theta \times F_{\text{tension}}$$

$$\textcircled{2} \quad F_{\text{gravity}} = \cos \theta \times F_{\text{tension}}$$

Now, if we simply divide equation  $\textcircled{1}$  by equation  $\textcircled{2}$ , we'll be able to discount the force of the tension:

$$\frac{\sin \theta}{\cos \theta} = \frac{F_{\text{hand}}}{F_{\text{gravity}}}$$

This is equal to the following:

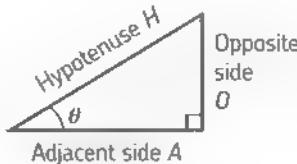
$$\tan \theta = \frac{F_{\text{hand}}}{F_{\text{gravity}}}$$

That means we can then represent the force of the hand in terms of the force of gravity and the angle of the string!

$$F_{\text{hand}} = \tan \theta \times F_{\text{gravity}}$$

## WAIT A SECOND, WHAT'S ALL THIS SINE AND COSINE STUFF?

If you've never studied trigonometry, don't worry—it's not too difficult to understand. Trigonometry is simply the study of the relationship between the length of a triangle's sides and its angles, especially right triangles. Because we often split forces and velocities into their horizontal and vertical parts, we'll use trigonometry frequently.



Let's look at the example below. Consider a right triangle with an angle of  $\theta$ .

Sine, cosine, and tangent (the three main trigonometric functions) are simply representations of the ratios of the three sides of this triangle.

The sine of the angle theta ( $\sin \theta$ ) is equal to the ratio of the opposite side ( $O$ ) to the hypotenuse ( $H$ ). In an equation, it looks like this:

$$\sin \theta = \frac{O}{H}$$

The other trigonometric functions are simply representations of different ratios! For example, the cosine of theta ( $\cos \theta$ ) is equal to the ratio of the adjacent side ( $A$ ) to the hypotenuse, and the tangent of theta ( $\tan \theta$ ) is the ratio of the opposite side to the adjacent side. The equations look like this:

$$\cos \theta = \frac{A}{H}$$

$$\tan \theta = \frac{O}{A}$$

If you have trouble remembering these different ratios and what they mean, try using the mnemonic device **SOHCAHTOA**.

$$\sin = O / H, \cos = A / H, \tan = O / A$$

Whenever you're confused about whether to use sine, cosine, or tangent, just think about SOHCAHTOA, the magic triangular island of trigonometry.



## NEWTON'S FIRST LAW OF MOTION



Newton's first law of motion states, "An object continues to maintain its state of rest or of uniform motion unless acted upon by an external net force." An isolated object in outer space, where no gravity is being exerted, will eternally stay at rest or travel with uniform velocity unless another force is imposed on it. A stationary object can have forces acting on it—however, the sum of these forces must be equal to zero. For example, a stationary object sitting on a desk is subject to the downward pull of gravity. The object remains stationary because it receives a vertical upward force from the desk, yielding a resultant force of zero.

Now that we understand the forces acting on a stationary object, we can move on to understanding what happens when the net force on an object is *not* zero.

## NEWTON'S SECOND LAW OF MOTION

When a force is imposed on an object, that object starts moving with a uniform acceleration proportional to the net force applied and inversely proportional to its mass. Assuming the vector of a force imposed on the object is  $F$ , the acceleration of the object is  $a$ , and the mass of the object is  $m$ , the second law of motion yields the following equation:

$$F = ma$$

Mass is a quantity that has only a magnitude, so it is a scalar quantity. However, recall that force and acceleration are vectors—so pay special attention to the acceleration of the object and the orientation of the force. They will be in the same direction!

The radio-controlled car you saw on page 49 moves in a square and attains a uniform velocity while it travels in a straight line. At this time, the net force on the car is zero. However, when the car turns around a corner, a force must be exerted to change the direction of its velocity. This is an important distinction: Acceleration does not have to change the *magnitude* of a velocity! It can simply change the *direction* of a velocity!

## THE ORIENTATION OF VELOCITY, ACCELERATION, AND FORCE

According to the second law of motion, the orientation of acceleration always matches the orientation of the force. However, the orientation of velocity does not directly correspond to the orientation of either the force or the acceleration. From the relationship between acceleration and velocity (explained on page 52) comes the following equation:

$$\text{change in velocity} = \text{acceleration} \times \text{time}$$

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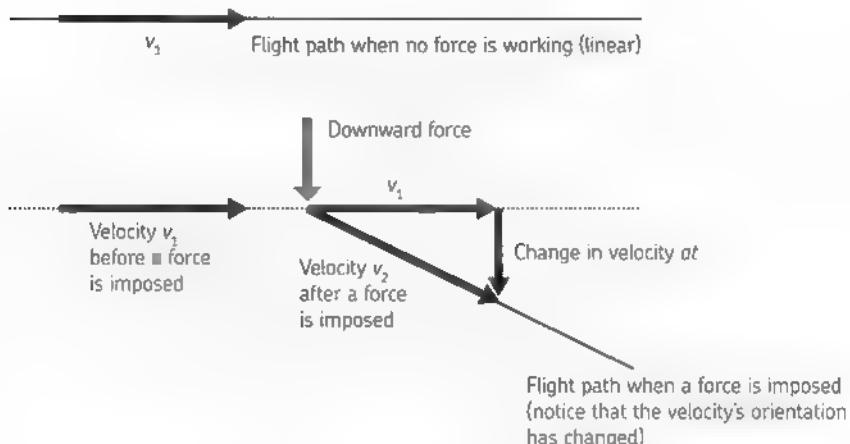
This means that the orientation of the change in velocity matches the orientation of acceleration! It's a subtle distinction, but an important one.

Let's look at an example. Suppose there is an object in motion at constant velocity  $v$ . When no force is acting on the object, it moves in a straight line at velocity  $v_1$ , according to the first law of motion. If a vertical force is imposed on the object for time  $t$ , how would the object's velocity change? Assuming that the acceleration created by the force is  $a$  and the velocity after the force is imposed is  $v_2$ , you can derive the following equation:

$$v_2 - v_1 = at$$

OR

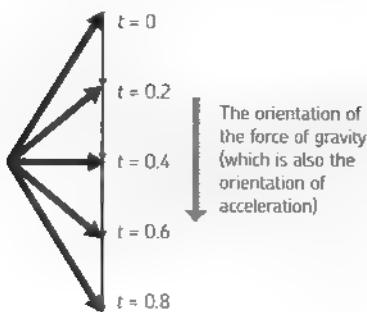
$$v_2 = v_1 + at$$



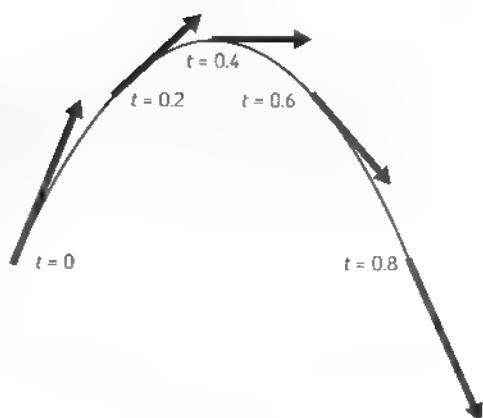
Thus, the addition of a force changes the direction of an object's motion. We can easily predict this object's motion by splitting  $v_2$  into its constituent horizontal and vertical parts. Its horizontal velocity must be equal to  $v_1$ , as there has been no force in the horizontal direction. The change in the object's vertical velocity is simply  $at$ !

In the example of throwing a ball on page 75, the force of gravity continues to act on the ball, even when the ball is moving upward. When the ball is rising in the air, its vertical velocity is decreasing due to the force of gravity. Once it starts falling, it gains velocity downward. The ball's horizontal velocity does not change; only its vertical velocity varies. The ball's motion follows the shape of a parabola, as shown in the following figure.

The velocity of the ball



Path of the ball



Notice how the horizontal component of this vector does not change!

## AN OBJECT DOES NOT HAVE ITS OWN FORCE



Those who have not studied physics tend to think, "An object in motion has a force." This is a common but incorrect notion. As we learned in Chapter 1, force is generated between paired elements whose movement affects each other. An object in motion does not have an internal force that causes it to stay in motion—it's simply the result of the first law of motion.

Let's look at the example of a ball being thrown up in the air. The ball receives a force from the hand until the moment it leaves the hand. (In response, due to the law of action and reaction, the hand receives a force from the ball—but this force has nothing to do with the ball's motion.) Once the ball leaves the hand, it only receives the force of gravity from the earth. The force on the ball from the hand does not remain after the ball leaves the hand.

## THE UNIT FOR FORCE

Newton's second law gives us the unit for force:

$$\text{force} = \text{mass} \times \text{acceleration}$$

In this equation, the unit for mass is kilograms (kg), while the unit for acceleration is meters per second squared ( $\text{m/s}^2$ ). Therefore, the unit for force is equal to  $\text{kg} \times \text{m/s}^2$ . To represent this more easily, we can use a unit called a newton (N):

$$1 \text{ newton} = 1 \text{ (kg} \times \text{m/s}^2\text{)}$$

You can use newtons to represent forces. As you can probably guess, this unit is named after the great Isaac Newton, who established the foundations of physics. A force of 1N is equivalent to the force required for accelerating an object with a mass of 1 kg by  $1 \text{ m/s}^2$ .

# MEASURING MASS AND FORCE

How can we determine the mass of an object?

Mass can be measured with a scale, which takes into account the fact that the force of gravity working on an object (that is, its weight) is proportional to its mass. Mass that is measured based on gravity is referred to as *gravitational mass*.

However, mass that is calculated using Newton's second law represents a measurement of the resistance of an object against acceleration; this mass has no direct relation to gravity. Mass as calculated by Newton's second law (mass = force / acceleration) is referred to as *inertial mass*.

Inertial mass can be measured by combining Newton's second law and the law of action and reaction. First, we need an object with a known mass (we'll call it the *reference object* and label it  $m_1$  in our diagram). Then, we'll arrange the object whose mass we want to measure (we'll call it the *measurement object* and label it  $m_2$  in our diagram) and the reference object so that their forces work on each other through a collision. In this collision, there are no external forces working on the objects.

At this time, the forces of the reference object and the measurement object working on each other are subject to the law of action and reaction. That is, they must be equal:

If  $F_1 = m_1a_1$  and  $F_2 = m_2a_2$ , we know that  $F_1 = F_2$ , due to the law of action and reaction. Therefore, we can express that relationship like so:

$$m_1a_1 = m_2a_2$$

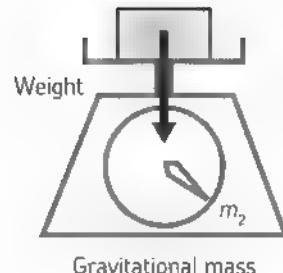
Since we're trying to solve for  $m_2$ , our measurement object, we'll rearrange that equation as follows:

$$m_2 = \frac{m_1a_1}{a_2}$$

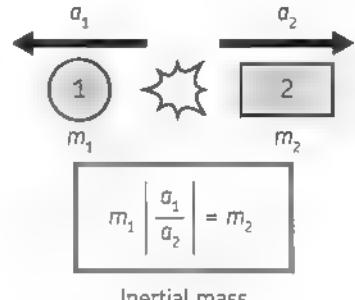
Of course, these accelerations are actually in opposite directions, so we'll consider their magnitude alone.

The acceleration of an object can be found by measuring the distance the object travels and the time it takes to travel that distance. If you have these measurements, you can find the inertial mass of the measurement object.

Although experiments have shown that gravitational mass is the same as inertial mass, Newton's Laws don't say that this *has* to be the case. Our understanding of this relationship comes from Einstein, who founded general relativity on the *equivalence principle*—the idea that inertial and gravitational mass are the same. This is still an active area of research.



Gravitational mass



Inertial mass

Once we've determined the mass of the objects in the collision, we can determine the force they've applied to each other. As the force causes the object to accelerate, we can measure this acceleration. We can then substitute this value into the following equation to determine an exact value of the force we've applied:

$$\text{mass} \times \text{acceleration} = \text{force}$$

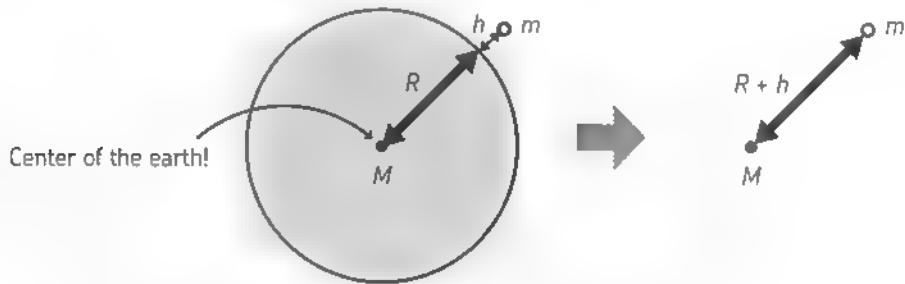
## DETERMINING WEIGHT



The force of gravity from the earth acting on an object with mass  $m$  is expressed as follows:

①  $F = mg$

In this equation,  $g$  is the magnitude of gravitational acceleration—about  $9.8 \text{ m/s}^2$  when measured near the ground surface. This relationship is derived from the equation for universal gravitation.



Consider an object with mass  $m$  located at an altitude  $h$  above the earth.

Assume that the earth is a perfect sphere with radius  $R$ , mass  $M$ , and a uniform density. Doing this, we can also assume that the gravity generated outside the surface of the earth by the entire globe is equivalent to the gravity of a point with mass equivalent to  $M$ . Using the equation that describes universal gravitation, which we saw on page 43, we can calculate the forces and acceleration due to the earth's gravitational pull.

Therefore, the magnitude of gravity from the earth acting on an object is equal to the value expressed below:

$$F = G \frac{Mm}{(R + h)^2}$$

Also note that the force of gravity on an object near the earth's surface (where  $h = 0$ ) is as follows:

$$F = G \frac{Mm}{R^2} \quad \text{where} \quad G \frac{M}{R^2} = g$$

Since we know that force here is also equal to mass times acceleration, we can set this equation equal to ①.

**NOTE** Remember from page 43 that  $G$  is the universal gravitational constant.

$$mg = G \frac{Mm}{R^2}$$

$$g = G \frac{M}{R^2}$$

The radius of the earth is about  $6.38 \times 10^6$  m, and its mass is about  $5.98 \times 10^{24}$  kg. Using these values, you can calculate the value of  $g$ , the acceleration of an object due to gravity:

$$g = G \frac{M}{R^2} = 6.67 \times 10^{-11} \times \frac{5.98 \times 10^{24}}{(6.38 \times 10^6)^2} \approx 9.8 \text{ m/s}^2$$

This is gravitational acceleration—notice that it does not depend on the mass of the smaller object ( $m$ ). Strictly speaking, because the earth is not a perfect sphere, gravitational acceleration close to the earth's surface varies slightly, depending on the location. Even so, you can safely approximate this value as  $9.8 \text{ m/s}^2$ .

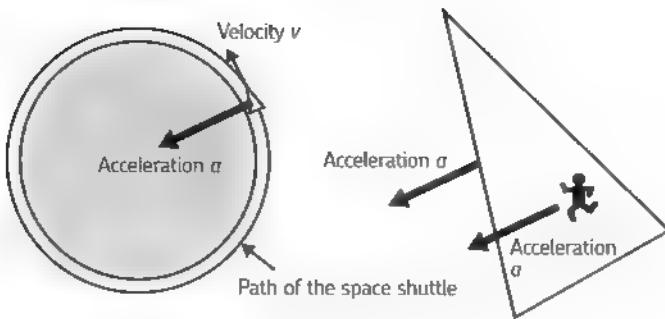
Now try to find the magnitude of gravitational acceleration at a point in the orbit of a space shuttle going around the earth. A space shuttle travels about 300 to 500 km from the earth's surface.

Assume  $h = 500$  km above the earth's surface.  $R + h = (6.38 \times 10^6 \text{ m}) + (0.5 \times 10^6 \text{ m}) = 6.88 \times 10^6 \text{ m}$ . Using this calculation, you can find the acceleration due to gravity at this altitude:

$$g = G \frac{M}{(R + h)^2} = 6.67 \times 10^{-11} \times \frac{5.98 \times 10^{24}}{(6.88 \times 10^6)^2} \approx 8.4 \text{ m/s}^2$$

In other words, a space shuttle is affected by gravity that is about 86 percent ( $8.4 / 9.8 = 0.86$ ) the strength of the gravity working on the earth's surface. Since the distance from the earth to a traveling space shuttle is about one-tenth of the radius of the earth, it is only reasonable to assume that the space shuttle is still heavily affected by the earth's gravity.

Then why does it feel like there is no gravity inside a space shuttle? It is because the shuttle is always "falling" as it is pulled by the earth's gravity. Einstein theorized that if the cable holding an elevator breaks, a person inside the falling elevator would find himself in a weightless environment much like outer space. Just like an elevator with a broken cable, the space shuttle's acceleration is oriented toward the center of the earth due to gravity. However, it always falls with a velocity oriented perpendicular to the direction of gravity; it does not move directly downward.



For this reason, the space shuttle travels around the earth along a circular (or, more specifically, elliptical) path. The feeling of so-called zero-gravity is created because the space shuttle and everything inside it, including the astronauts, are "falling" at the same gravitational acceleration.

## UNDERSTANDING PARABOLIC MOTION



We examined a ball in flight on page 75—that ball's motion is something we call *parabolic motion*. Here, let's take a more in-depth look at the ball's flight using some real numbers and equations.

In the figure below, the distance in the horizontal direction is expressed as  $x$ , the vertical direction as  $y$ , and the ball's mass as  $m$ . The force of gravity on the ball works downward along the  $y$ -axis, with a magnitude of  $mg$ . Represented in terms of its constituent parts, the force vector on the ball is expressed as follows:

$$F = (0, -mg)$$

↑ force in  $x$  direction      ↓ force in  $y$  direction

Similarly, we can represent acceleration in terms of component elements as  $a = (a_x, a_y)$ . We know the following:

Acceleration in the  $x$  direction is  $a_x = 0$ .

Acceleration in the  $y$  direction is  $a_y = -g$ .

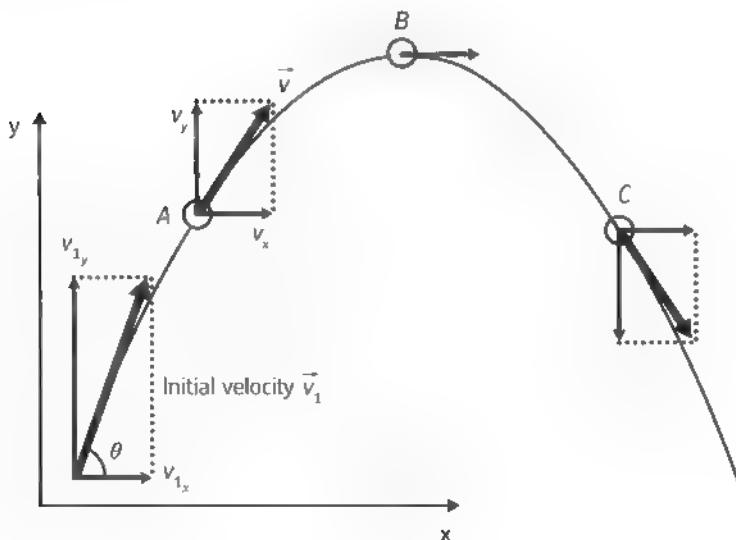
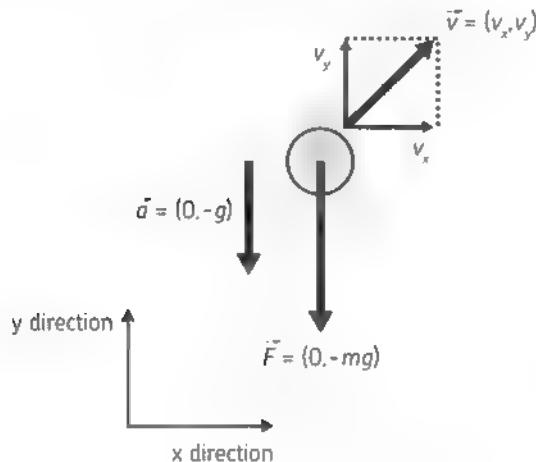
In short, the ball has a uniform velocity in the  $x$  direction, and uniform accelerated motion occurs in the  $y$  direction.

Given that we know these values, we can find the velocity of the ball at any time. When the ball is released,  $t = 0$  and the velocity for throwing it is  $\vec{v}_1 = (v_{1_x}, v_{1_y})$ , from rule ①, you get:

$$v_{2_x} = v_{1_x}$$

$$v_{2_y} = v_{1_y} - gt$$

These equations indicate that velocity does not change in the x direction, but it does change downward in the y direction by  $-9.8 \text{ m/s}$  in one second ( $gt = -9.8 \text{ m/s}^2 \times 1 \text{ s} = -9.8 \text{ m/s}$ ).



Next, let's find the location of the ball. Let's split it into constituent parts in the x and y directions:

$$x = v_{1_x} t$$

$$y = v_{1_y} t - \frac{1}{2} g t^2$$

Now, if there were only some way to eliminate the time variable in this second equation. Perhaps we should rearrange that first equation!

$$t = \frac{x}{v_{1_x}}$$

Substituting that into the second equation, we get the following:

$$y = v_{1_y} \left( \frac{x}{v_{1_x}} \right) - \frac{1}{2} g \left( \frac{x}{v_{1_x}} \right)^2$$

This is actually a quadratic function, and it will show a parabola when plotted. The origin is at the point where the ball leaves the hand.

From this equation, you can tell where the thrown ball will land. Actually, we can take the term  $\left( \frac{x}{v_{1_x}} \right)$  out of this equation like so:

$$y = \frac{x}{v_{1_x}} \left( v_{1_y} - \frac{1}{2} g \left( \frac{x}{v_{1_x}} \right) \right)$$

And given that we know that the ball's landing point should be where  $y = 0$  and  $x \neq 0$ , let's set  $y$  equal to 0:

$$0 = \frac{x}{v_{1_x}} \left( v_{1_y} - \frac{1}{2} g \left( \frac{x}{v_{1_x}} \right) \right)$$

$$v_{1_y} = \frac{1}{2} g \left( \frac{x}{v_{1_x}} \right)$$

Given this equation, we can solve for  $x$ , the distance that the ball travels!

$$\textcircled{1} \quad x = \frac{2v_{1_x}v_{1_y}}{g}$$

By rewriting the expression and assigning  $\theta$  to the angle of the throw, you can find the angle that would enable the ball to reach the farthest point for a given velocity. The initial velocity can be expressed as follows:

$$v_1 = (v_{1_x}, v_{1_y}) = (v_1 \cos \theta, v_1 \sin \theta)$$

You can use this to re-define the landing point in equation ①:

$$x = \frac{2 \times v_1 \cos \theta \times v_1 \sin \theta}{g} = \frac{v_1^2 \sin 2\theta}{g}$$

This value reaches a maximum when  $\sin(2\theta) = 1$ .\* Therefore, when throwing a ball at this fixed velocity, the ball reaches the farthest distance when thrown at an angle of 45 degrees.

## USING CALCULUS TO FIND ACCELERATION AND VELOCITY

### WARNING: CALCULUS AHEAD!

Normally, the velocity of an object changes over time. In this example, let's say  $\Delta t$  is a short amount of time during which we can assume the velocity is constant. Then we get the following approximation, where  $\Delta x$  represents the displacement created in time  $\Delta t$ :



$$v = \frac{\Delta x}{\Delta t}$$

In this equation, the smaller the value you assign to  $\Delta t$ , the more precise approximation you can get for the velocity. In an experiment,  $\Delta t$  can only have a finite value. Thus, we can only find the velocity to be an average value. But mathematically, we can assume a case where  $\Delta t$  infinitely approaches zero. In other words, we can define the velocity for a given moment as follows:

$$\bullet \quad v = \lim_{\Delta t \rightarrow 0} \frac{\Delta x}{\Delta t} = \frac{dx}{dt} \quad \text{This is the very definition of a derivative.}$$

The same is true with acceleration. Let's assign  $\Delta v$  to a short amount of time  $\Delta t$ , during which the velocity can be assumed to be virtually constant. Then acceleration  $a$  is expressed as follows:

$$a = \frac{\Delta v}{\Delta t}$$

When acceleration is not uniform, we can make the change in  $t$  infinitely small:

$$a = \lim_{\Delta t \rightarrow 0} \frac{\Delta v}{\Delta t} = \frac{dv}{dt}$$

This represents acceleration for a given instant. Also note that by substituting expression ① in this expression, we get the following:

$$a = \frac{d}{dt} \left( \frac{dx}{dt} \right) = \frac{d^2 x}{dt^2}$$

\* If you were confused by the math in these equations, remember that  $\sin(2\theta) = 2 \sin \theta \cos \theta$ .

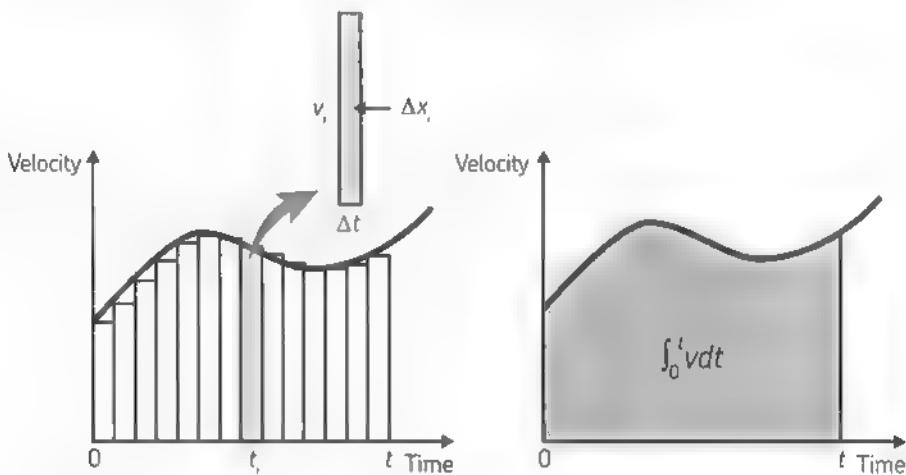
Thus, acceleration can be expressed as the second derivative of the displacement. Newton's second law ( $F = ma$ ) can be expressed in differential calculus as follows:

$$m \frac{dv}{dt} = F \quad \text{or} \quad m \frac{d^2x}{dt^2} = F$$

## USING THE AREA OF A V-T GRAPH TO FIND THE DISTANCE TRAVELED BY AN OBJECT



Next, let's examine how we can find the distance an object travels if we already know its velocity (see page 54). When the velocity is uniform, we know that the following equation holds true, and we can find the distance traveled ( $\Delta x$ ) over a change in time ( $\Delta t$ ).



For a velocity that's changing magnitude, we can find an approximation by summing up the distances traveled in  $\Delta t$ -long time segments. In other words, we divide the time interval between point 0 and point  $t$  into  $n$  segments, assign  $t_i$  to the  $i$ th point in time, and assign  $v_i$  to the velocity at that moment.

Express the time as  $\Delta t$ , the velocity as  $v$ , and the distance as  $\Delta x_i$  to yield the following equation:

$$x = v_1 \Delta t + v_2 \Delta t + \dots + v_i \Delta t + \dots + v_n \Delta t$$

The distance  $x$  traveled between point 0 and point  $t$  can be found using the following approximation:

$$x = \sum_{i=1}^n v_i \Delta t$$

When the rectangle is divided into infinitely small segments to allow  $\Delta t$  to infinitely approach zero (when  $n$  or the number of segments approaches infinity), the results will be much more precise:

$$x = \lim_{n \rightarrow \infty} \sum_{i=1}^n v_i \Delta t = \int_0^t v dt$$

This is the very definition of integration. This equation shows that you can find the distance traveled using integral calculus representing the area under the v-t graph.

Now, given uniform accelerated motion with acceleration  $a$ , velocity  $v_1$  at time  $t = 0$ , and velocity  $v_2$  at time  $t$ , we know the following:

$$a = \frac{v_2 - v_1}{t}$$

From this equation, we can immediately tell that  $v_2 = v_1 + at$ , or rule ① on page 85. Now that we have an equation for final velocity as a function of time, we may substitute it into the integral equation to calculate displacement:

$$x = \int_0^t (v_1 + at) dt$$

Since  $v_1$  and  $a$  are constants, this is a relatively simple integral to evaluate:

$$x = [v_1 t + \frac{1}{2}at^2]_0^t$$

The lower limit of  $t = 0$  makes evaluating this equation quite simple:

$$x = v_1 t + \frac{1}{2}at^2$$

We have just derived a rule that should look very familiar to you!



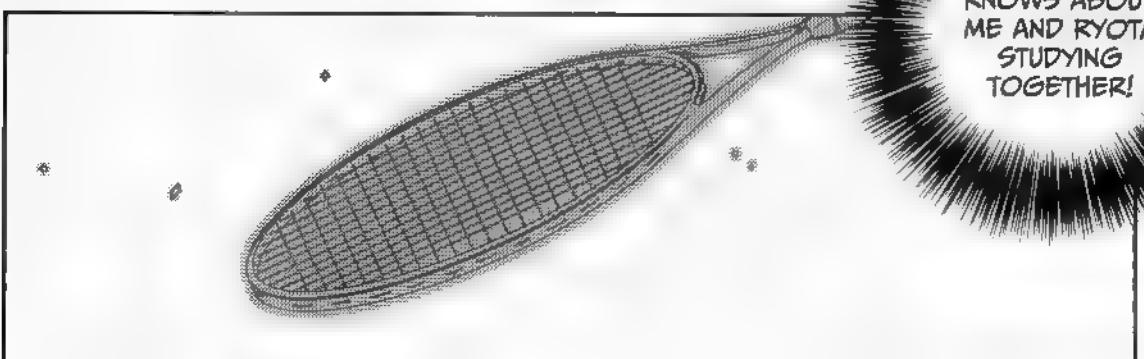
3

MOMENTUM



## MOMENTUM AND IMPULSE





UNDERSTANDING  
MOMENTUM



A BALL IN MOTION HAS AN ATTRIBUTE CALLED MOMENTUM.

IS THAT WHAT'S CREATING A FORCE AGAINST MY RACKET?

WHEN A FAST-MOVING BALL STRIKES YOUR RACKET, THE MOMENTUM OF THE BALL IMPACTS THE RACKET.

AND SO INDEED, IT CREATES A FORCE.

BAM

IMPACT!

...MOMENTUM

BUT MOMENTUM AND VELOCITY ARE DIFFERENT THINGS, AREN'T THEY?

YES, MOMENTUM IS DEFINED AS:

MOMENTUM = MASS X VELOCITY

$$p = mv$$

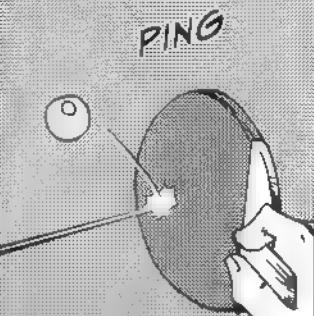
I THOUGHT ALL WE  
NEEDED TO CALCULATE  
MOMENTUM WAS THE  
VELOCITY.

I DIDN'T REALIZE  
WE NEEDED AN  
OBJECT'S MASS  
TOO!

WELL, JUST  
THINK ABOUT IT  
A BIT.

EVEN IF THEIR  
VELOCITY WERE  
EQUIVALENT, A  
TENNIS BALL...

SHH TOCK



AND A PING-  
PONG BALL HAVE  
MOMENTUM OF  
VERY DIFFERENT  
MAGNITUDES.

...YEAH, A PING-  
PONG BALL  
WOULDN'T HURT  
VERY MUCH IF IT HIT  
SOMEONE'S HEAD.

WHAT?

MEGUMI'S DAYDREAM—  
TENNIS COURT MURDER: MYSTERIOUS  
BRUISE ON THE VICTIM'S HEAD

NOW...TO  
COLLECT  
HER LIFE  
INSURANCE.

ARE YOU STILL  
RESENTFUL  
ABOUT THAT  
INCIDENT?

HMM...  
f

THE BALL  
WASN'T  
THAT BIG.

NO NO, IT WASN'T  
ANYTHING LIKE  
THAT!

I WAS SIMPLY  
TRYING TO HELP  
YOU, NINOMIYA-SAN.  
IT LOOKED LIKE A  
LOT OF WORK FOR  
ONE PERSON.

GETTING  
SULKY...

OH, I'M JUST  
KIDDING.

YOU KNOW,  
NONOMURA-KUN,  
YOU TEND TO GET  
SULKY RATHER  
EASILY.

NOT AT ALL...

HERE SHE  
GOES  
AGAIN...

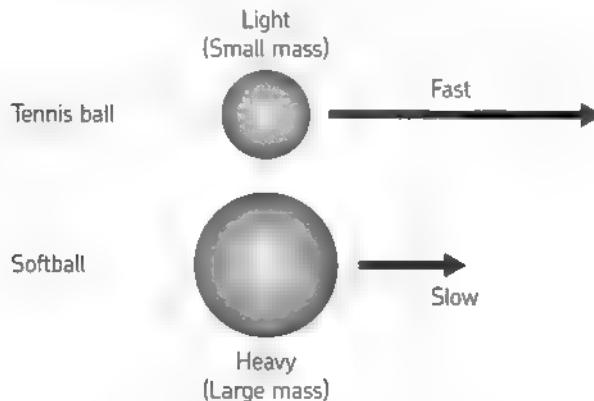
# LABORATORY

## DIFFERENCE IN MOMENTUM DUE TO A DIFFERENCE IN MASS



To help you understand how momentum works, I've brought in a softball and a tennis ball.

Let's examine the momentum of a softball traveling slowly and a tennis ball traveling quickly.



Let me see, the softball is much heavier than the tennis ball, right?



Yes, of course. We know the following about the two balls:

$$m_{\text{softball}} > m_{\text{tennis ball}}$$

$$v_{\text{softball}} < v_{\text{tennis ball}}$$





However, we can't tell which ball has the greater momentum. Recall that momentum can be calculated as mass multiplied by velocity ( $p = mv$ ). We'd need to know numerical values to determine the difference precisely.



Well, I know that a tennis ball has a mass of about 60 g.



And a softball is about 180 g.



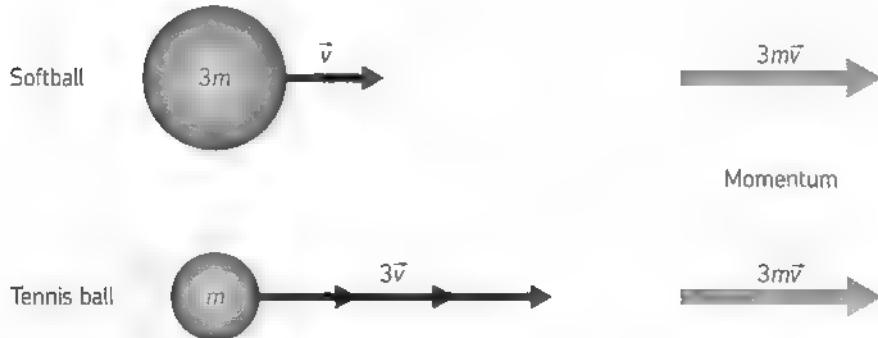
So we're almost there. It's 60 g versus 180 g—the mass of a softball is about three times as great as that of a tennis ball.



Given these new facts and the relationship  $p = mv$ , to have an equivalent momentum, the tennis ball must have a velocity three times as great as the softball.



Oh, I see.



CHANGE IN MOMENTUM  
AND IMPULSE

DO YOU  
UNDERSTAND HOW A  
BALL CAN IMPACT A  
RACKET

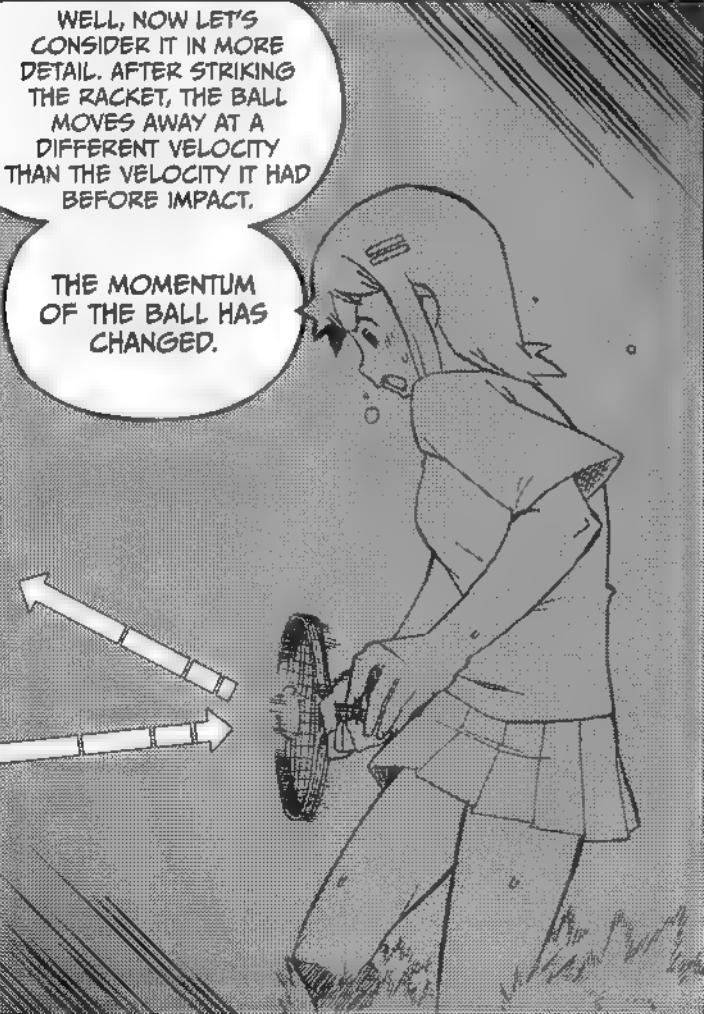
BECAUSE  
IT HAS  
MOMENTUM?

YES, QUITE  
CLEARLY.

WELL, NOW LET'S  
CONSIDER IT IN MORE  
DETAIL. AFTER STRIKING  
THE RACKET, THE BALL  
MOVES AWAY AT A  
DIFFERENT VELOCITY  
THAN THE VELOCITY IT HAD  
BEFORE IMPACT.

THE MOMENTUM  
OF THE BALL HAS  
CHANGED.

LET'S EXAMINE THE  
CHANGE IN MOMENTUM  
USING NEWTON'S  
SECOND LAW.



OH, I THINK I  
REMEMBER THAT  
ONE. IT GOES  
LIKE THIS:

$$F = ma$$

FORCE = MASS X ACCELERATION



RIGHT, AND YOU  
KNOW THAT  
ACCELERATION  
IS SIMPLY THE  
CHANGE IN  
VELOCITY OVER  
TIME. SO...



IF ACCELERATION  
IS CONSTANT, WE  
CAN REPLACE THAT IN  
NEWTON'S SECOND  
LAW TO EQUAL

$$\text{FORCE} = \text{MASS} \times \frac{\text{CHANGE IN VELOCITY}}{\text{TIME}}$$

OR

$$F = m \times \frac{(v_2 - v_1)}{t}$$

LET ME SEE...  
SO THAT  
MEANS...



CAN YOU  
TELL THE  
DIFFERENCE?

$$\text{MASS} \times \text{CHANGE IN VELOCITY} = \text{FORCE} \times \text{TIME}$$

$$m \times (v_2 - v_1) = Ft$$

IF WE REARRANGE  
THIS JUST A LITTLE BIT  
(BY MULTIPLYING EACH  
SIDE BY  $1$ ), WE GET THE  
FOLLOWING.



WELL, WHAT  
GOOD DOES  
THAT DO?

WE KNOW THAT MOMENTUM IS MASS MULTIPLIED BY VELOCITY.

SO MASS MULTIPLIED BY THE CHANGE IN VELOCITY IS REALLY JUST THE CHANGE IN MOMENTUM, PROVIDED THAT MASS  $m$  IS CONSTANT.

I SEE.

LET'S TAKE A LOOK AT THAT EQUATION AGAIN, AND THIS TIME WE'LL EXPAND THE TERMS ON THE LEFT SIDE.

$$mv_2 - mv_1 = Ft$$

CHANGE IN MOMENTUM = FORCE  $\times$  TIME

I SEE—THE CHANGE IN MOMENTUM IS EQUAL TO THE FORCE APPLIED TO THAT OBJECT MULTIPLIED BY TIME.

YES, FORCE MULTIPLIED BY TIME IS CALLED IMPULSE.

IMPULSE CAUSES THE MOMENTUM OF AN OBJECT TO CHANGE.

IN THE MOMENT THAT THE BALL IS IN CONTACT WITH THE RACKET, ITS MOMENTUM CHANGES. THIS IS THE FORCE YOU FEEL ON YOUR ARM.

AHA!

LET'S EXAMINE THE SCENARIO IN MORE SPECIFIC TERMS.

LET'S SAY THAT THE BALL'S MASS IS  $m$ , THE BALL'S VELOCITY BEFORE HITTING THE RACKET IS  $v_1$ , AND THE VELOCITY AFTER BEING STRUCK IS  $v_2$ .

POW!

AHHH

THE FORCE FROM THE RACKET IS  $F$ , AND THE TIME THAT THE RACKET AND BALL ARE IN CONTACT IS  $t$ .

MOMENTUM BEFORE STRIKING:  $mv_1$

MOMENTUM AFTER STRIKING:  $mv_2$

FORCE FROM RACKET:  $F$

TIME IN CONTACT:  $t$

BEFORE STRIKING

MOMENT OF STRIKING

AFTER STRIKING

LET'S FIGURE OUT THE MOMENTUM OF THE BALL BEFORE AND AFTER IT STRIKES THE RACKET.



HHHHHAAAAAA!  
HHHHHAAAAAA!



$p = mv$ , AS WE KNOW, SO

UHM...

THE MOMENTUM ( $p$ ) OF THE BALL BEFORE IT STRIKES THE RACKET IS  $mv_1$ .

AND THE MOMENTUM AFTER STRIKING THE RACKET IS  $mv_2$ ... SO THE VARIATION IS EQUAL TO  $mv_2 - mv_1$ , RIGHT?

CORRECT!

THE IMPULSE IS EXPRESSED AS  $Ft$ .

AND WE CAN GET THIS EQUATION BECAUSE WE KNOW THAT...

$$mv_2 - mv_1 = Ft$$

THE CHANGE IN MOMENTUM IS EQUAL TO IMPULSE.

IN FACT, THIS EXPRESSION IS NOTHING BUT ANOTHER WAY OF EXPRESSING NEWTON'S SECOND LAW,  $F = ma$ .

OH, YEAH?

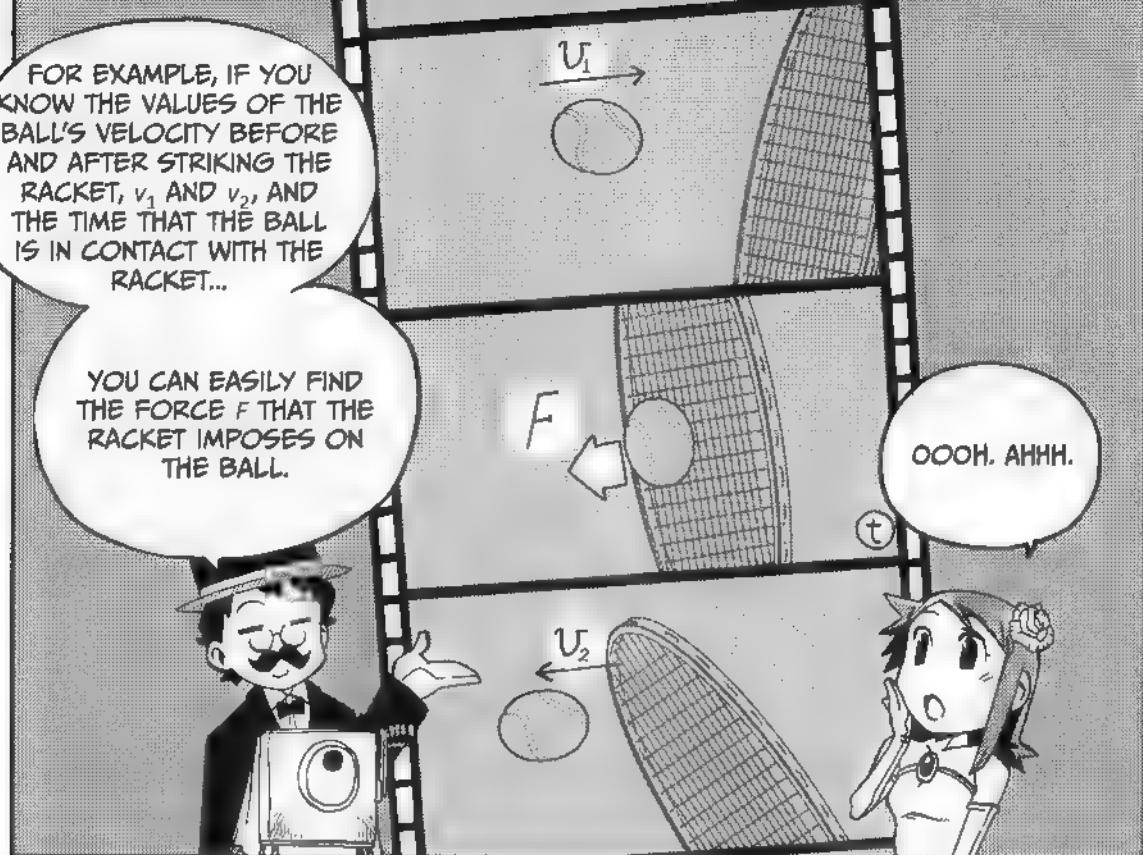
$$F = ma$$

$$mv_2 - mv_1 = Ft$$

BUT IT IS VERY USEFUL WHEN YOU WANT TO FIND THE CHANGE IN MOMENTUM FROM A KNOWN FORCE— OR TO FIND THE FORCE FROM A KNOWN CHANGE IN MOMENTUM.

FOR EXAMPLE, IF YOU KNOW THE VALUES OF THE BALL'S VELOCITY BEFORE AND AFTER STRIKING THE RACKET,  $v_1$  AND  $v_2$ , AND THE TIME THAT THE BALL IS IN CONTACT WITH THE RACKET...

YOU CAN EASILY FIND THE FORCE  $F$  THAT THE RACKET IMPOSES ON THE BALL.



# LABORATORY

## FINDING THE MOMENTUM OF A STROKE



Let's actually analyze this scenario, Ninomiya-san, and find out the force you're applying to the ball. During your match with Sayaka, I filmed your motion with a high-speed camera. We'll analyze a time when you returned her smash.



Here you go again. Yet another make-believe scenario.



This time, I really did shoot the footage.



What on earth . . . ?



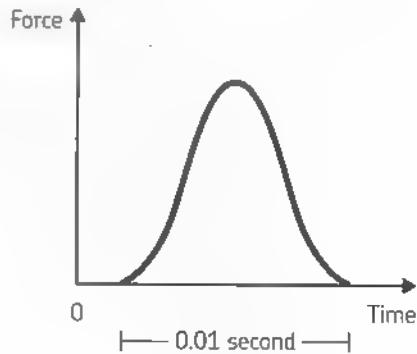
It's all in the name of science. Anyway, I analyzed the images and learned that the velocity of the ball when it hit the racket was about 100 km per hour, and you returned the ball at about 80 km per hour. And I measured the time that the ball was in contact with your racket—it was 0.01 second.



So we should have all the numbers we need!



Using these values, we can find the magnitude of the force your racket imposed on the ball. But it's actually not so simple. A graph of the force over time looks like this.

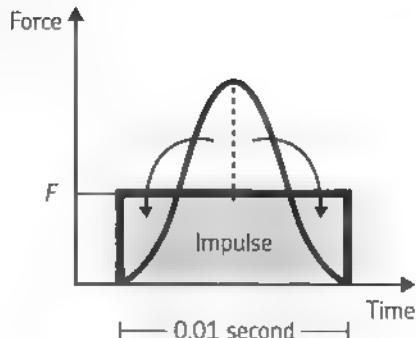




However, we'll assume an average magnitude of  $F$  in this example.



That makes the calculation much easier.



First, let's calculate the momentum of the ball before you hit it. The mass of a tennis ball is 0.06 kg. The velocity is negative 100 km per hour, as viewed from the direction of the return. As  $1 \text{ km} = 1000 \text{ m}$ , and  $1 \text{ hour} = 3600 \text{ seconds}$ , we'll convert our units for velocity into meters per second (m/s) as follows:  $1 \text{ km/h} = 1000 \text{ m} / 3600 \text{ s}$ . The calculation looks like this:

$$\frac{-100 \text{ km}}{\text{h}} \times \frac{1000 \text{ m}}{\text{km}} \times \frac{1 \text{ h}}{3600 \text{ s}} = -27.8 \frac{\text{m}}{\text{s}}$$

$$p = mv$$

$$p = 0.06 \text{ kg} \times -27.8 \text{ m/s}$$

$$p = -1.7 \text{ kg} \times \text{m/s}$$



Now we know the ball's initial momentum. It's a little weird that the value is negative, but I guess it just indicates the direction from my point of view.



So now let's calculate the momentum of the ball after you've struck it. Given that the velocity of the ball afterwards is 80 km/h, and its orientation is positive, the result is as follows:

$$\frac{80 \text{ km}}{\text{h}} \times \frac{1000 \text{ m}}{\text{km}} \times \frac{1 \text{ h}}{3600 \text{ s}} = 22.2 \frac{\text{m}}{\text{s}}$$

$$p = mv$$

$$p = 0.06 \text{ kg} \times 22.2 \text{ m/s}$$

$$p = 1.3 \text{ kg} \times \text{m/s}$$



Now we can find the change in these two values.



The change in momentum can be calculated like so:

$$1.3 \text{ kg} \times \text{m/s} - (-1.7 \text{ kg} \times \text{m/s}) = 3.0 \text{ kg} \times \text{m/s} = \Delta p$$

So that's the change in the ball's momentum. And since the force was working for 0.01 seconds, we can figure out the force, using this equation:

$$\Delta p = Ft \quad \text{or} \quad \frac{\Delta p}{t} = F$$



In our example, that means  $(3.0 \text{ kg} \times \text{m/s}) / 0.01 \text{ s} = 300\text{N}$ . That's the force on my racket, I bet.



Yes, that's it. Since you probably don't know what a newton feels like, let's find the equivalent force generated by 1 kg weight, assuming that 1 kg is about equal to 9.8N:

$$300\text{N} \times \frac{1 \text{ kg}}{9.8\text{N}} = 30.6 \text{ kg}$$

But why is the force generated by one kilogram 9.8 newtons . . . ?

Nevermind, I think I see. We did that before . . .  $F = ma$ . Acceleration due to gravity is  $9.8 \text{ m/s}^2$ .



Wow, that's a lot to lift!



Well, remember, the force from gravity is constant—this is just momentary. And you're using your muscles in a very different way, in a different direction.



## THE CONSERVATION OF MOMENTUM

NEWTON'S THIRD LAW AND THE CONSERVATION OF MOMENTUM



I UNDERSTAND HOW A BALL HAS MOMENTUM. BUT I'M CONFUSED—WHERE DOES THE MOMENTUM LOST FROM THE BALL GO?

LET'S EXAMINE IT IN DETAIL.



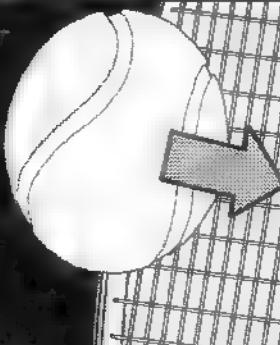
IT'S THAT WEIRD GUY AGAIN.

MOMENTUM IS EXCHANGED BETWEEN ANY OBJECTS THAT ARE IMPOSING FORCE ON EACH OTHER! IT'S NOT JUST WHEN YOU HIT A TENNIS BALL!

AND MOREOVER, THE SUM OF THE MOMENTUM EXCHANGED IS CONSTANT AND PREDICTABLE.

SO...

THE FOLLOWING IS TRUE—ALL OF THE MOMENTUM LOST FROM THE BALL IS TRANSFERRED TO THE RACKET.



DO YOU MEAN THE TOTAL MOMENTUM DOES NOT CHANGE?

LET'S TALK  
ABOUT IT USING  
A SIMPLE  
EXAMPLE.

HERE ARE A  
100 YEN COIN  
AND A 500 YEN  
COIN.

PLEASE TRY TO HIT  
THE 500 YEN COIN  
WITH THE 100 YEN  
COIN.

WELL...  
I'LL TRY.

SHAZAM!

CLINK

FLICK

THE 500 YEN COIN  
MOVED FORWARD,  
AND THE 100 YEN  
COIN'S VELOCITY  
REVERSED  
DIRECTION.

500

THIS HAPPENS  
BECAUSE THE 100 YEN  
COIN HAS MOMENTUM  
WHEN IT HITS THE  
500 YEN COIN, RIGHT?

FORCE FROM THE  
100 YEN COIN TO THE  
500 YEN COIN

WHEN ONE OBJECT  
STRIKES ANOTHER,  
WE KNOW THAT THE  
TWO FORCES IN PLAY  
MUST BE EQUAL AND IN  
OPPOSITE DIRECTIONS.

THAT'S NEWTON'S  
THIRD LAW, THE LAW  
OF ACTION AND  
REACTION.

FORCE FROM THE  
500 YEN COIN TO THE  
100 YEN COIN

AH, NEWTON AGAIN!

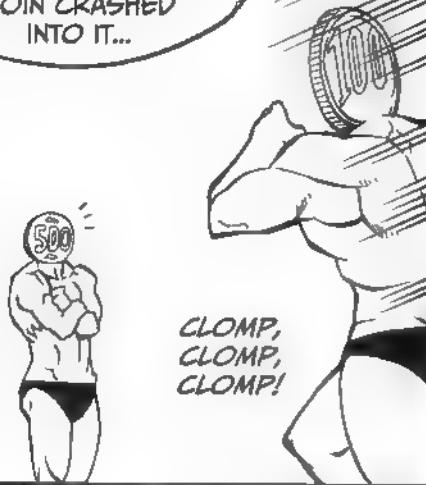
AS THE CHANGE IN  
MOMENTUM IS EQUAL  
TO THE FORCE  
MULTIPLIED BY THE TIME  
( $\Delta p = Ft$ ), THE CHANGE IN  
MOMENTUM FOR EACH  
OBJECT SHOULD BE  
THE SAME!

IN OTHER  
WORDS...

THE SUM OF THE CHANGE  
IN THE MOMENTUM OF THE  
100 YEN COIN AND THE  
CHANGE IN THE MOMENTUM  
OF THE 500 YEN COIN  
MUST EQUAL ZERO!  
( $\Delta p_{100} + \Delta p_{500} = 0$ )

$$\uparrow + \downarrow = 0$$

WHEN THE 500 YEN COIN WAS AT REST, ITS MOMENTUM WAS 0. THEN THE 100 YEN COIN CRASHED INTO IT...



AS FORCE WAS IMPOSED, THE MOMENTUM OF BOTH COINS CHANGED.



SO THE SUM OF THE MOMENTUM OF THE TWO COINS AFTER IMPACT IS THE SAME AS THE INITIAL MOMENTUM OF THE 100 YEN COIN.



WE CALL THIS THE LAW OF CONSERVATION OF MOMENTUM.



CONSERVATION OF MOMENTUM? WHAT DOES THAT MEAN?



WELL, LET'S LOOK  
AT THE RULE,  
MOMENTUM IS  
CONSERVED.

FIRST, READ IT  
ALOUD.

Change in momentum of the 100 yen coin  
= Momentum after the collision – its initial momentum

This, in turn, must offset the following:

Change in momentum of the 500 yen coin  
= Momentum after the collision – its initial momentum

MM-HMM.

SINCE THE SUM OF  
THEIR CHANGE IN  
MOMENTUM MUST  
EQUAL ZERO,  
WE KNOW THE  
FOLLOWING:

$$\Delta p_{100} + \Delta p_{500} = 0$$

$$(m\vec{v}_2 - m\vec{v}_1) + (M\vec{V}_2 - M\vec{V}_1) = 0$$

I SEE.

REWRITING THAT  
EXPRESSION EVEN  
FURTHER, WE GET

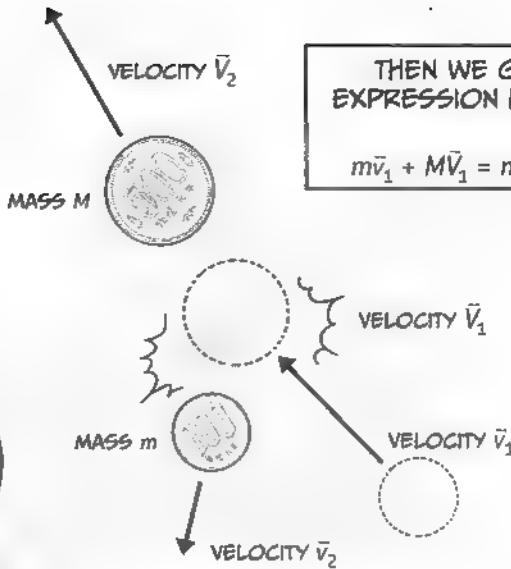
$$m\vec{v}_1 + M\vec{V}_1 = m\vec{v}_2 + M\vec{V}_2$$

Initial momentum = Final momentum

IT'S A LITTLE  
CONFUSING IN  
TEXT.

ASSUME THAT THE MASS OF THE 100 YEN COIN IS  $m$ , AND THE MASS OF THE 500 YEN COIN IS  $M$ . LET'S REPRESENT THE VELOCITY OF THE 100 YEN COIN AS  $v$ , AND THE 500 YEN COIN AS  $V$ .

AND AS BEFORE, WE'LL REPRESENT BEFORE AND AFTER VELOCITIES AS  $v_1$  AND  $v_2$  AND  $V_1$  AND  $V_2$ , RESPECTIVELY.



THEN WE GET AN EXPRESSION LIKE THIS:

$$m\bar{v}_1 + M\bar{V}_1 = m\bar{v}_2 + M\bar{V}_2$$

AND WE KNOW THAT  $v_1 = 0$ , SINCE THE 500 YEN COIN WAS AT REST, SO WE CAN FURTHER SIMPLIFY THE EQUATION TO THE FOLLOWING:

$$m\bar{v}_1 = m\bar{v}_2 + M\bar{V}_2$$

AH, THAT MAKES PERFECT SENSE!

THE TOTAL MOMENTUM FOR THE SYSTEM IS THE SAME BEFORE AND AFTER THE COLLISION. IT DOESN'T INCREASE OR DECREASE!



NOW YOU KNOW ABOUT A SPECIFIC APPLICATION OF THE LAW OF ACTION AND REACTION.

IT'S THE CONSERVATION OF MOMENTUM.



# LABORATORY

## OUTER SPACE AND THE CONSERVATION OF MOMENTUM



Let's think about outer space for our next example of the conservation of momentum.



What is this, space camp?



Sigh. Let's just suppose you are an astronaut, Ninomiya-san. During vehicle repairs outside the space craft, your tether has become disconnected, leaving you floating away from your space shuttle. All you have in your hand is the wrench you've been using to repair your ship. How can you get back to your ship?



Maybe I can swim back.



Oh, ho ho ho, it's quite impossible to "swim" in a vacuum. Recall the first law of motion: An object at rest tends to stay at rest unless a force is imposed. No matter how hard you move your arms and legs, you won't have anything to push against. You'd just be rotating around your center of gravity, flailing your arms around.



Oh no! Things are really looking bad!



Never give up hope! Your physics knowledge may save your life. You have that wrench, remember? Throw it in the direction opposite to the rocket. Thanks to the conservation of momentum, you will move.



Really? I'm gonna make it?



To confirm that this works, let's assume that you're at rest, in outer space. Then let's set the wrench's mass as  $m$  and assume you throw it away from you at velocity  $v$ . Your mass and subsequent velocity are represented by  $M$  and  $V$ .



Since we are starting with no momentum, the momentum of both objects afterward must equal zero, right?



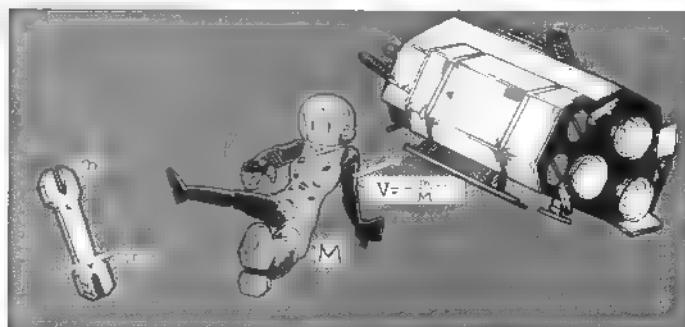
Indeed! Given the law of conservation of momentum, the sum of the momentum of both bodies should equal zero. If we put that in an equation, it looks like this:

$$mv + MV = 0$$

To find  $V$ , or your velocity back to your ship, we rearrange the equation:

$$V = -\frac{m}{M} \times v$$

This value is negative because it indicates that your motion is in the opposite direction of the wrench.





Can you see why you'd want to throw the wrench as hard as you could?  
The faster its  $v$ , the faster your  $V$ .



Yes, that makes sense.



Let's assign some numeric values and try to predict things. We'll say the wrench has a mass of 1 kg and give you a mass of 60 kg with that heavy space suit on. Assuming that the tool's velocity when thrown is 30 km/h, we get the following:

$$V = -\frac{1 \text{ kg}}{60 \text{ kg}} \times 30 \text{ km/h} = -0.5 \text{ km/h}$$

So that would be your velocity back to the ship.



Let's say I have a whole toolbox. If I throw tools one after another, will I move faster?



That's a great idea. Yes, you would go faster and faster that way. In fact, that's basically how a rocket moves. The exhaust that is belched out the rear of a rocket is equivalent to an object being thrown.



Gee, I never thought of it that way.



A rocket can continue to accelerate by belching exhaust continuously. As long as fuel continues to discharge, the rocket will accelerate. When the rocket stops discharging exhaust, the rocket's velocity becomes uniform.

## REAL-WORLD EXPLORATIONS OF IMPULSE



YOUR CHANGE IN MOMENTUM IS FIXED—YOU CANNOT ALTER IT. HOWEVER, YOU CAN REDUCE THE FORCE ON YOUR BODY FROM THE LANDING.

YOU'D MAKE THE TIME THAT YOU RECEIVE THE FORCE FROM THE GROUND AS LARGE AS POSSIBLE.

THAT SOUNDS PRETTY SIMPLE.

REALLY?  
HOW WOULD I  
DO THAT?

APPLYING THE LAW OF  $\Delta p = I$  = IMPULSE, WE GET CHANGE IN MOMENTUM  $(m \times \Delta v)$  EQUALS FORCE MULTIPLIED BY THE TIME. NOW, TIME IN THIS CASE IS THE TIME THAT YOU'RE RECEIVING FORCE.

THIS EQUATION CAN BE REWRITTEN AS:

$$F = \frac{m \times \Delta v}{t}$$

THAT MEANS THE LARGER THE  $t$  VALUE, THE SMALLER THE  $F$  VALUE YOU RECEIVE.

I SEE!

JUST THINK ABOUT GYM  
CLASSES. FOR THE HIGH  
JUMP, YOU USE SOFT  
FOAM MATS TO BREAK  
YOUR FALL, RIGHT?



WITHOUT THEM, YOU  
COULDN'T DARE  
JUMP SO HIGH.

WE COMMONLY THINK,  
"MATS ABSORB IMPACT  
BECAUSE THEY'RE SOFT  
AND FLUFFY."

BUT FROM THE VIEW  
OF MECHANICS, THEY  
ARE EXTENDING THE  
TIME YOU RECEIVE  
FORCE.

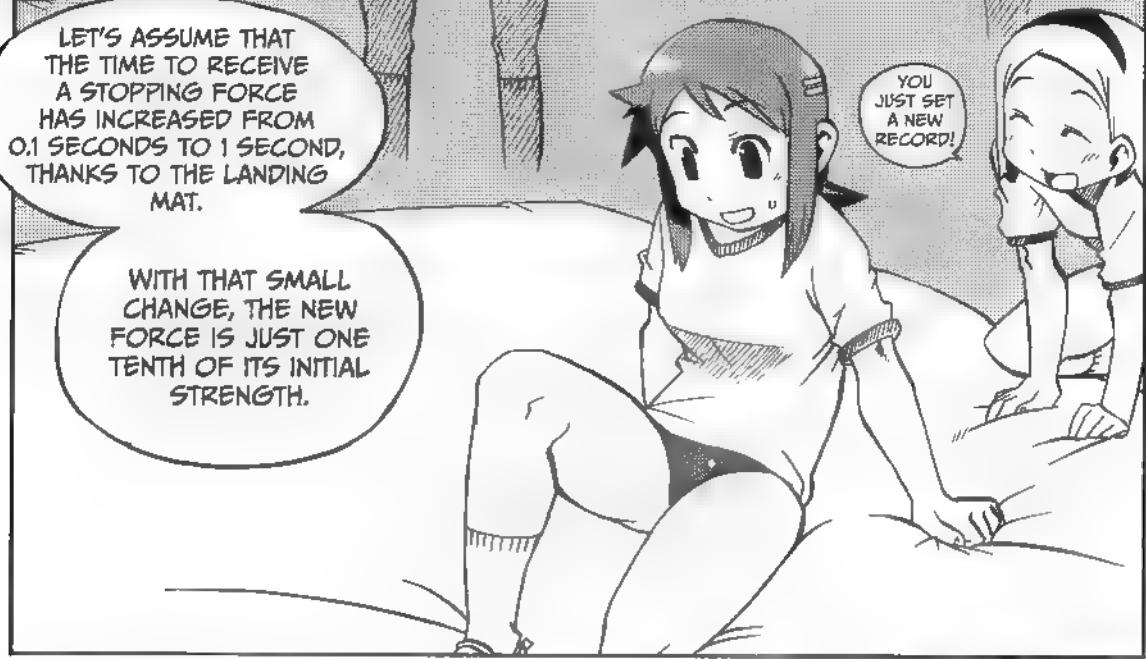
**FOSBURY  
FLOP!**

THAT SHEDS NEW  
LIGHT ON THE  
MATTER.

LET'S ASSUME THAT THE TIME TO RECEIVE A STOPPING FORCE HAS INCREASED FROM 0.1 SECONDS TO 1 SECOND, THANKS TO THE LANDING MAT.

WITH THAT SMALL CHANGE, THE NEW FORCE IS JUST ONE TENTH OF ITS INITIAL STRENGTH.

YOU JUST SET A NEW RECORD!



A CAT CAN SAFELY LAND WHEN IT JUMPS FROM A HIGH PLACE. PERHAPS ITS FLEXIBLE BODY HELPS TO EXTEND THE TIME OF IMPACT.

THAT'S RIGHT. BECAUSE THE CAT BENDS ITS LIMBS, THE TIME THE CAT'S BODY RECEIVES FORCE IS INCREASED SLIGHTLY. BUT THIS RESULTS IN MUCH LESS FORCE ON IMPACT WITH THE GROUND.

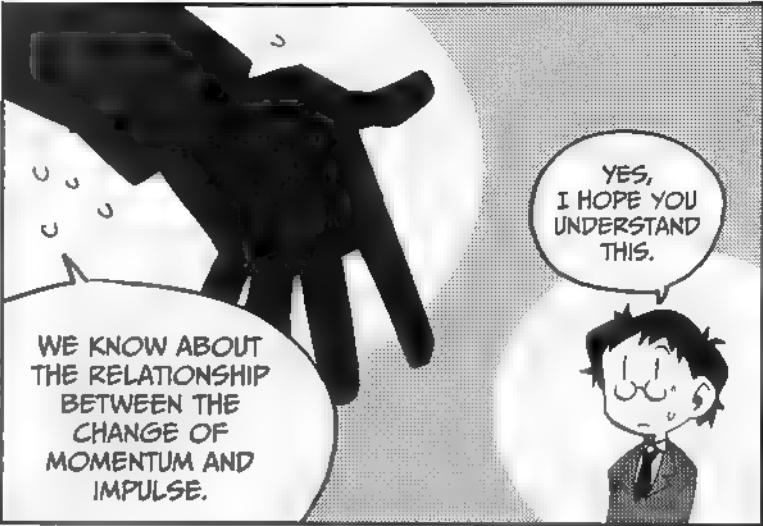
THINKING LIKE THIS...



PHYSICS IS APPLICABLE TO MANY SITUATIONS IN DAILY LIFE.

NOW...

## IMPROVING MEGUMI'S SERVE



THAT MEANS I CAN APPLY IT TO MY TENNIS GAME!

I SEE.

RECALL HOW WE EXAMINED THE MOMENTUM OF A STROKE.

YES!

HERE SHE GOES!

GIVEN THE IMPORTANCE OF CHANGING A BALL'S MOMENTUM, I WANT TO FIND OUT A BETTER WAY TO SERVE!

THE FATAL SERVICE OF MEGUMI NINOMIYA THAT COULD SMASH AN ELEPHANT!

GRRRR  
IS THAT REALLY THE KIND OF SERVE YOU WANT TO DELIVER?





WELL, IF THAT'S THE CASE, WE SHOULD TALK ABOUT YOUR MATCH WITH SAYAKA. YOU TWO ARE EVENLY MATCHED AND SEEM TO HAVE THE SAME PHYSICAL STRENGTH.



BUT KODA-SAN WAS USING THE SPRING OF HER BODY WHILE SHE SERVED. HER SERVE IS MUCH MORE POWERFUL THAN YOUR OWN.



ARE YOU SAYING I'M NOT AS GOOD AS SAYAKA?



I JUST MEAN THAT'S ONE AREA TO IMPROVE. YEOW!



ALL RIGHT THEN. I'LL EXAMINE MY SERVE IN THE CONTEXT OF MECHANICS.



SOUNDS GOOD TO ME.



PUFF  
PUFF  
PUFF



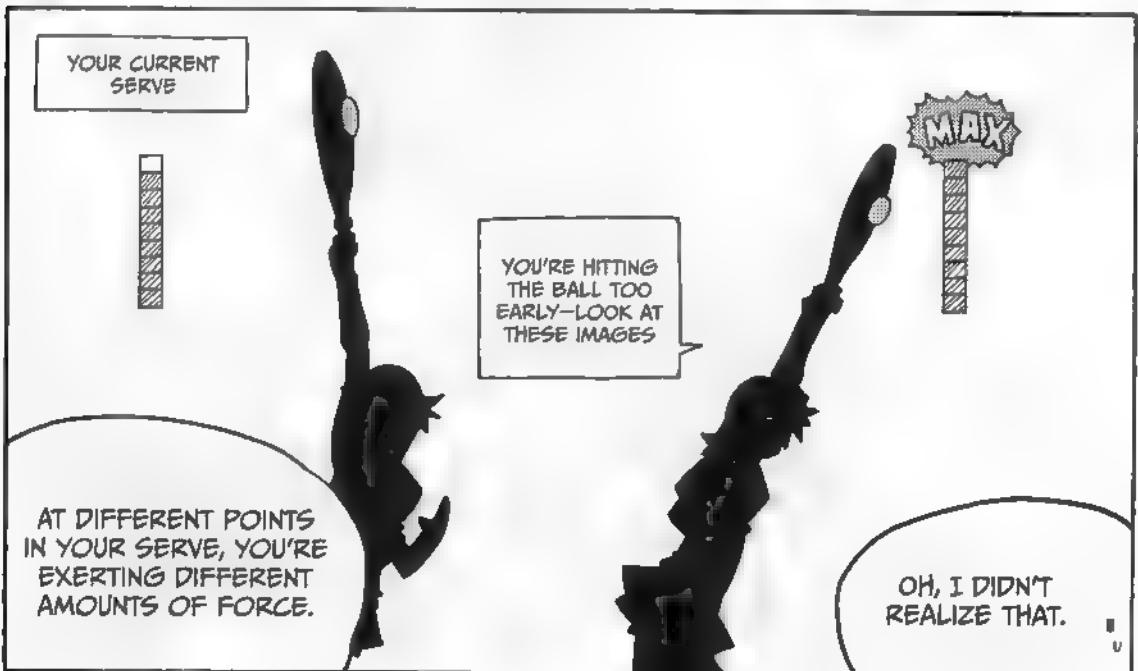
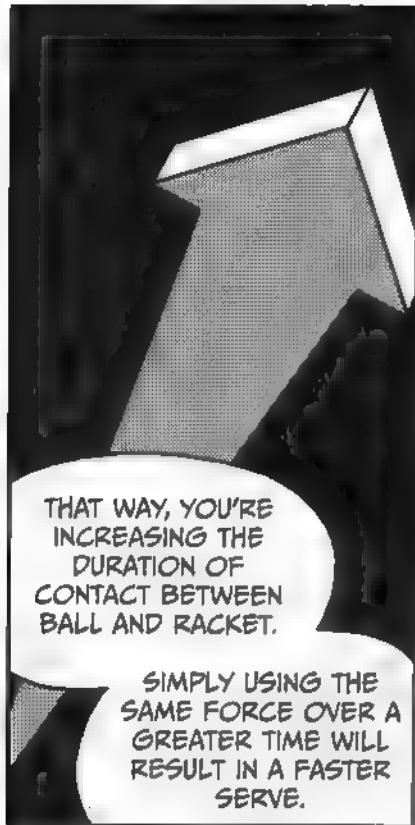
WELL, WE KNOW THAT CHANGE IN MOMENTUM EQUALS FORCE MULTIPLIED BY TIME, SO ONE IDEA FOR IMPROVING YOUR SERVE...



IS TO IMPOSE A FORCE ON THE BALL FOR AS LONG AS POSSIBLE.



WE'RE OFTEN TOLD TO HIT THE BALL WITH ALL OUR MIGHT!



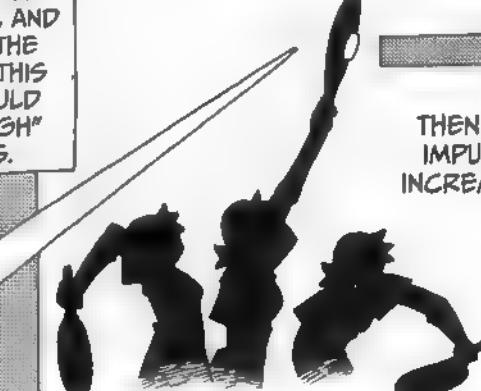
SO, BY MAKING YOUR BODY MORE FLEXIBLE AND HITTING THE BALL AT THE RIGHT TIME, YOU CAN MAXIMIZE THE FORCE YOU EXERT ON THE BALL AND THE DURATION OF IMPACT.

FLEXIBLE, EH...

JUST WAITING A BIT LONGER TO STRIKE THE BALL COULD HELP A LOT.

HIT THE BALL LIKE AN OVERHEAD SMASH, AND TRY TO EXTEND THE TIME OF IMPACT. THIS IS WHY YOU SHOULD "FOLLOW THROUGH" YOUR STROKES.

THEN THE IMPULSE INCREASES!



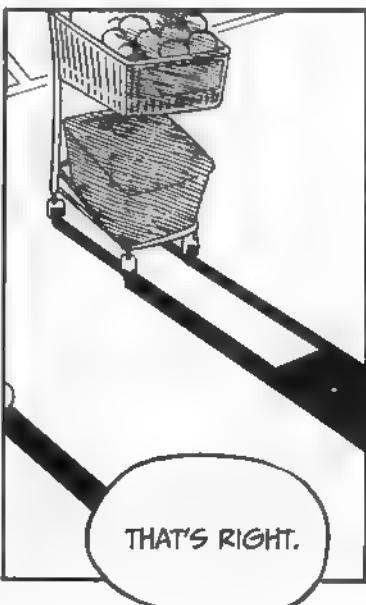
OF COURSE, TENNIS IS A COMPLICATED GAME, AND WE CAN'T REPRESENT EVERYTHING SO SIMPLY...

STILL, THE PRINCIPLE OF CHANGE IN MOMENTUM = IMPULSE EXPLAINS HOW THE BALL MOVES.

YEAH.

AND DESPITE THE PHYSICS INVOLVED, YOU STILL HAVE TO KEEP YOUR EYE ON THE BALL DURING THE GAME...





## MOMENTUM AND IMPULSE



Momentum is a quantity representing the magnitude and orientation of the motion of an object. Assuming that an object with mass  $m$  and velocity  $\vec{v}$  has momentum  $\vec{p}$ , the relationship among them can be represented as follows:

$$\vec{p} = m\vec{v}$$

Since velocity is a vector, momentum is also a vector. An object's momentum and velocity will have the same orientation.

As mentioned in Chapter 2, an object in motion does not have force inside of it—it has momentum. The momentum of an object varies as an external force is imposed on it, and a change in momentum is called *impulse*. So, let's derive the relationship between momentum and impulse, starting by examining Newton's second law.

Suppose a ball with mass  $m$  hits a racket. Assume  $\vec{v}_1$  for the velocity of the ball before it hits the racket and  $\vec{v}_2$  for the velocity of the ball after it hits the racket. Also assume  $\vec{F}$  for the force imposed on the ball from the racket.

Given Newton's second law,

$$\vec{F} = m\vec{a}$$

the ball undergoes acceleration  $\vec{a}$ . Generally, force  $\vec{F}$  is not constant, but for our purposes, let's assume that  $\vec{F}$  is constant at its average value (see page 118). If  $\vec{F}$  is assumed to be constant, then acceleration  $\vec{a}$  is also constant. If we let  $t$  equal the time that the ball receives a force from the racket, acceleration  $\vec{a}$  can be expressed as follows:

$$\vec{a} = \frac{(\vec{v}_2 - \vec{v}_1)}{t}$$

We can substitute this value for  $\vec{a}$  into Newton's second law:

$$\vec{F} = m \times \frac{(\vec{v}_2 - \vec{v}_1)}{t}$$

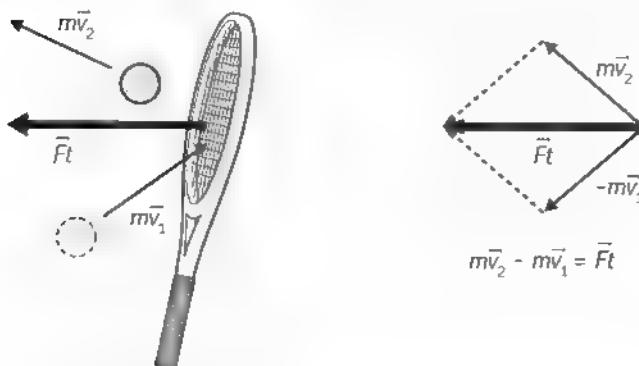
If we multiply both sides by  $t$ , we get the following:

$$m\vec{v}_2 - m\vec{v}_1 = \vec{F}t$$

The expression  $m\vec{v}_2 - m\vec{v}_1$  represents the object's change in momentum. When we call quantity  $\vec{F}t$  the impulse, the following relationship is true:

change in momentum = impulse

Note that momentum  $m\vec{v}_2 - m\vec{v}_1$  and impulse  $\vec{F}t$  follow the rule of composition of vectors, as shown in the figure below.



We can see from the way this equation is derived that the relational expression of change in momentum and impulse is an application of Newton's second law, in a situation where force is constant. When I said the equation for impulse is "nothing but another way of expressing Newton's second law" on page 115, this is what I meant.

## IMPULSE AND MOMENTUM IN OUR LIVES

As we learned on page 129, the relationship between the change in momentum and impulse is useful when we want to determine how to reduce the impact of a collision.

In order to minimize the force imposed on an object while the object is in motion and up until the moment the motion stops, we must maximize the collision period because of the following relationship:

$$\text{change in momentum of an object} = \text{imposed force} \times \text{time duration of imposed force}$$

Assume you are jumping from a high place, and your velocity immediately before landing is  $v$ . Once you land and are in a stationary state, the change in your momentum is  $mv$ . (How do we know this? Well, at rest, you must have no momentum at all, since you have no velocity:  $m = 0 = 0$ .) This change in momentum is generated by the force from the ground, and your body must withstand this *impact force* that it receives. If we assume  $F$  for the impact force and  $t$  for the period of time the force is being withstood, the following expression is true:

$$mv = \vec{F}t$$

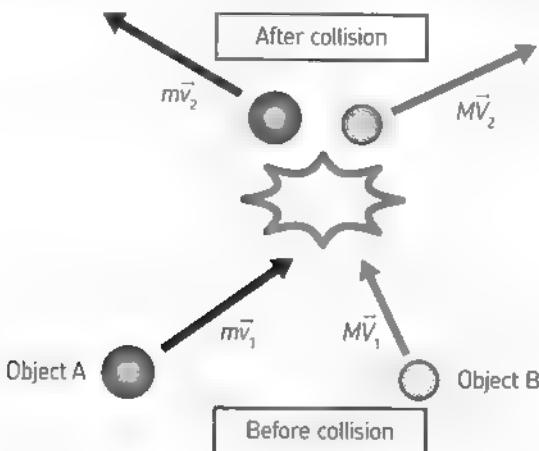
When  $mv$  is constant,  $F$  becomes smaller as  $t$  becomes larger. For example, the mats used for the high jump function as a tool for extending the time period  $t$  from the point where the body's impact on the mat starts to the point where momentum  $mv$  becomes zero. As the body sinks into the mat, the jumper continues to receive force  $F$ . As  $Ft$  is constant, the greater time period  $t$ , the smaller force  $F$  becomes.

We can find examples of the fact that a change in momentum equals impulse everywhere in our daily lives. When catching a ball, we tend to unconsciously withdraw our hand.

We are actually trying to reduce the force by extending the time duration from the point of the ball's contact with the hand to the point where the ball stops. Similarly, the gloves used in baseball and boxing extend the time period of the impact and reduce the force. *Ukemi* (the judo art of reacting to an attack by falling strategically), the crumple zones of modern cars, and air bags are all designed to reduce the impact of the force accompanying the change in momentum by extending the time of collision. Similarly, the safety ropes used in rock climbing are designed to stretch when a climber falls, so the collision time will be longer. This also prevents a sudden force from being imposed on the climber's waist. It would be very dangerous to use a rope that does not stretch instead of a special rope for climbing.

## DERIVING THE LAW OF CONSERVATION OF MOMENTUM

Let's derive the law of conservation of momentum by applying our knowledge that the change in momentum equals impulse to two colliding objects.



As in the preceding figure, assume that objects A and B collide without any external force being imposed and without the dissipation of any momentum in their impact.

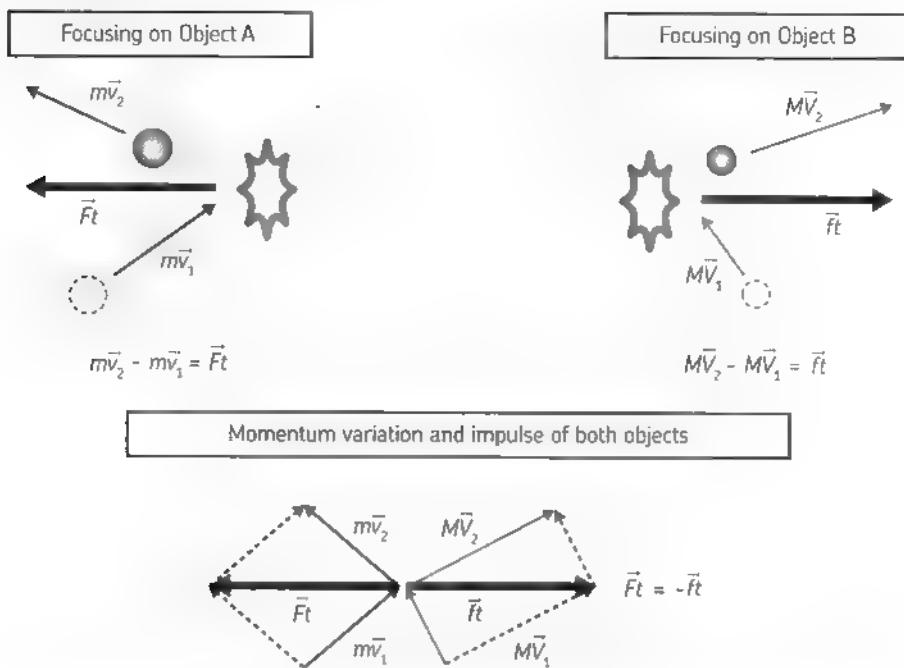
First, let's focus on object A (the object on the left in the preceding figure). Assume  $m$  for the mass of object A and  $\vec{v}_1$  and  $\vec{v}_2$  for its velocity before and after collision. Also assume  $\vec{F}$  for the force received by object A from object B. The relational expression showing that the change in momentum equals impulse can then be written as follows:

$$m\vec{v}_2 - m\vec{v}_1 = \vec{F}t$$

Here,  $t$  represents the time of the collision of objects A and B, and force approaches a constant value. Create an equation for object B (the object on the right in the preceding figure) using the knowledge that the change in momentum equals impulse. Assume  $M$  for the mass of object B,  $\vec{V}_1$  and  $\vec{V}_2$  for the velocity before and after collision, and  $\vec{f}$  for the force received by object B from object A:

$$M\vec{V}_2 - M\vec{V}_1 = \vec{f}t$$

Note that the collision time is equal for both objects. It must be, since A cannot touch B without B touching A. But wait, why is the force the same for both as well? It's simply the law of action and reaction— $\vec{F} = -\vec{F}$ !



Substitute the previous two expressions representing the relationship between the change in momentum and impulse into the preceding expression to get the following:

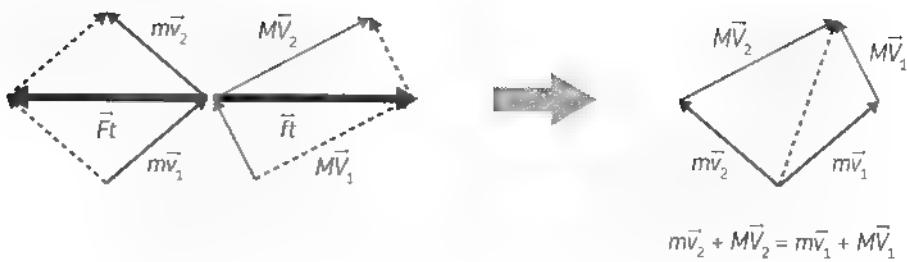
$$MV_2 - MV_1 = -(mv_2 - mv_1)$$

Consolidate this expression:

$$mv_2 + MV_2 = mv_1 + MV_1$$

The momentum of the objects before impact must be equal to their momentum afterward. This is the law of conservation of momentum shown on page 125.\*

\* We can omit the vector signs in the case of a collision between objects moving on the same straight line.



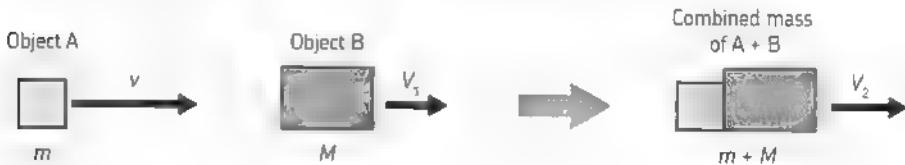
These equations can be represented as vectors, as shown in the preceding figure on the left. The vectors can be rearranged to combine the change in momentum and impulse for objects 1 and 2, respectively, with the law of action and reaction, to get the vector on the right.

## ELASTIC AND INELASTIC COLLISION

It's important to note that problems involving collision cannot always be solved using the law of conservation of momentum. In the real world, we must consider the dissipation of kinetic energy and other factors. We'll learn more about kinetic energy in the next chapter.

However, we can apply the law of conservation of momentum in two ideal situations—a perfectly *elastic* collision, or a perfectly *inelastic* one. The first example here was a perfectly elastic one—two objects that move separately after their collision, losing no energy in the process. Think of an elastic collision as something like two super-balls hitting each other—in the real world, the collision of atoms is said to be elastic. Now let's take a look at an example to better understand what an inelastic collision is.

An *inelastic collision* is one where the colliding objects combine to form a singular object in motion after their collision. An example of this would be a tackle in football, where after striking each other, the two players travel together as one.



In this example, assume that object A with mass  $m$  and velocity  $v$  is combined with object B with mass  $M$  and velocity  $V_1$ . At this time, we get the following equation:

$$p = (m + M)V_2$$

The two objects achieve velocity  $V_2$  after they are combined. Applying the law of conservation of momentum, we get the following equation:

$$mv + MV_1 = (m + M)V_2$$

Therefore, the velocity after the two objects are combined is as follows:

$$\frac{mv + MV_1}{m + M} = V_2$$

## UNITS FOR MOMENTUM

Let's think about the unit we use to measure momentum. Recall that force is represented in newtons (N), but momentum doesn't use a special unit of measure. But from the equation momentum = mass  $\times$  velocity, you can tell that:

$$\begin{aligned}\text{units for momentum} &= \text{units for mass} \times \text{units for velocity} \\ &= (\text{kg}) \times (\text{m/s}) = (\text{kg} \times \text{m/s})\end{aligned}$$

You can also use the fact that a change in momentum equals impulse to determine the units for momentum. The units for momentum are the same as the units for impulse. Therefore, the following expression is also true:

$$\begin{aligned}\text{units for momentum} &= \text{units for impulse} = \text{units for force} \times \text{units for time} \\ &= (\text{N}) \times (\text{s}) = (\text{N} \times \text{s})\end{aligned}$$

This seems different from the units we just calculated, ( $\text{kg} \times \text{m/s}$ ). However, given ( $\text{N} = (\text{kg} \times \text{m/s}^2)$ ), you get:

$$(\text{kg} \times \text{m/s}^2) \times (\text{s}) = (\text{kg} \times \text{m/s})$$

Both units are identical. We've learned that the units for momentum are ( $\text{kg} \times \text{m/s}$ ), or ( $\text{N} \times \text{s}$ ).

## LAW OF CONSERVATION OF MOMENTUM FOR VECTORS



Since momentum is a vector, to follow the law of conservation of momentum, we must consider the orientation of momentum as well. In other words, when momentum is conserved, we must conserve both its orientation and its magnitude. Therefore, if the orientation of momentum changes (as in the example of a collision of coins on page 121), you need to calculate this change by dividing momentum into separate horizontal and vertical components, as vectors.

Assume a perfectly elastic collision in which object A collides with stationary object B, as shown in the following figure.

Assume  $m$  for the mass of object A,  $v_1$  and  $v_2$  for its velocity before and after the collision,  $M$  for the mass of object B, and  $V$  for its velocity after the collision. Place the x-axis on the vector representing the velocity of object A before the collision, assume  $\theta$  and  $\phi$  for the angles made by object A and object B after the collision, respectively, and assume  $v_1 = |v_1|$ ,  $v_2 = |v_2|$ ,  $V_2 = |V_2|$ .

We'll then split the velocities into their constituent parts, like so, in the form of  $v = (v_x, v_y)$ :

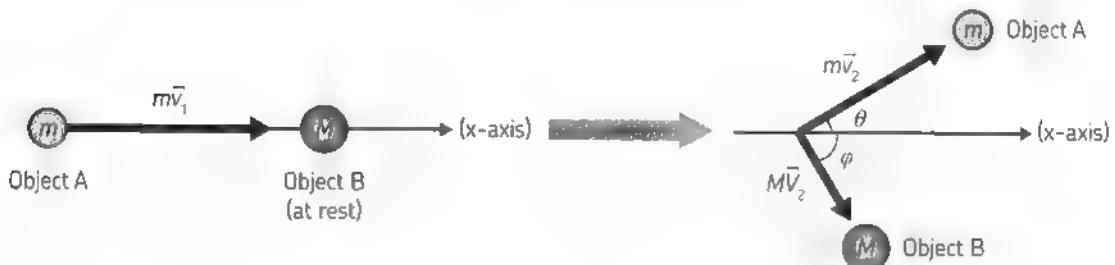
$$v = (v_1, 0), v_2 = (v_2 \cos \theta, v_2 \sin \theta), V_1 = (V \cos \varphi, -V \sin \varphi)$$

Now that we've done that, consider that the law of momentum must hold true in both the x and y directions. Note that the object initially has no momentum in the y direction. So that means that the following must be true:

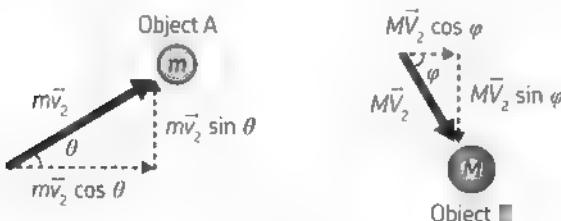
$$\text{For the x direction: } mv_1 = mv_2 \cos \theta + MV \cos \varphi$$

$$\text{For the y direction: } 0 = mv_2 \sin \theta - MV \sin \varphi$$

When a 500 yen coin collides with a 100 yen coin, the 100 yen coin often bounces backward. In this case,  $\theta > 90^\circ$ , so  $\cos \theta < 0$ . The following figure shows an example where  $\theta < 90^\circ$ .



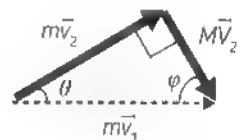
Let's see how we split the objects' momentum into horizontal and vertical parts.



If we place these head-to-tail, we can visually see what we already know: Momentum has been conserved in the system.

In other words, in the y direction, the momentum of objects 1 and 2 must offset each other. And the sum of their momentum in the x directions must equal  $\bar{mv}_1$ .

We need to know more than the law of conservation of momentum to predict the velocity and the angle at which the objects move after the collision. We'll look at this in more detail in the next chapter.



# LAW OF ACTION AND REACTION VS. LAW OF CONSERVATION OF MOMENTUM

## WARNING: CALCULUS AHEAD!



Using differential and integral calculus, we can easily derive the law of conservation of momentum. Assume  $v$  and  $m$  for the velocity and mass of object 1 and  $V$  and  $M$  for those of object 2. Suppose no external force is working on these objects. Assuming  $\vec{F}_{m \rightarrow M}$  for the force imposed on object 2 by object 1 and  $\vec{F}_{M \rightarrow m}$  for the force imposed on object 1 by object 2, we can apply Newton's second law as follows:

$$m \frac{d\vec{v}}{dt} = \vec{F}_{M \rightarrow m} \quad \text{and} \quad M \frac{d\vec{V}}{dt} = \vec{F}_{m \rightarrow M}$$

Substitute these two equations into the following equation for the law of action and reaction:

$$\vec{F}_{M \rightarrow m} = -\vec{F}_{m \rightarrow M}$$

The following will result:

$$m \frac{d\vec{v}}{dt} = -M \frac{d\vec{V}}{dt}$$

As mass is a constant, the above expression can be transformed into the following:

$$\frac{d(m\vec{v})}{dt} = -\frac{d(M\vec{V})}{dt}$$

Consolidate these two equations:

$$\frac{d}{dt} (m\vec{v} + M\vec{V}) = 0$$

This equation indicates that the sum of the momentum of objects 1 and 2 ( $m\vec{v} + M\vec{V}$ ) will not change over time. From this equation, you can derive the law of conservation of momentum:

$$m\vec{v} + M\vec{V} = \text{constant}$$

A constant derivative means that the momentum does not change! The law of conservation of momentum is derived from both the law of action and reaction and Newton's second law. So you can also say that the law of conservation of momentum stems from the law of action and reaction.

You can use the same method to derive the law of conservation of momentum for three or more objects.

## PROPULSION OF A ROCKET

In the Laboratory section on page 126, we learned that an astronaut in space will move in the opposite direction of an item he has thrown. This phenomenon occurs according to the same principles that drive rocket propulsion. A rocket increases its velocity by belching exhaust at a high rate out of its engine, and it moves in the opposite direction of its exhaust. Let's look into this phenomenon in depth.



First, assume that a stationary rocket in outer space discharges a small object with mass  $m$  at a velocity of  $v$ . Then assume  $M$  for the sum of mass of the small object and the rocket and  $V_1$  for the velocity of the rocket after the exhaust discharge. Given the law of conservation of momentum (and knowing that these velocities are in the exact opposite direction), you get the following equation:

$$0 = (M - m)V_1 - mv$$

$$\bullet \quad V_1 = \frac{mv}{M - m}$$

We've solved for the rocket's subsequent motion,  $V_1$ . Now, suppose this rocket discharges another object of mass  $m$  at *relative velocity* (velocity as viewed from the rocket)  $-v$  and in the same direction as the previous discharge. At this time, assuming  $V_2$  for the rocket's velocity and noting that the total mass of the rocket before and after discharging the second object is  $M - m$  and  $M - 2m$ , respectively, you get the following equation:

$$(M - m)V_1 = (M - 2m)V_2 + m(V_1 - v)$$

Note that the small object moves at a velocity of  $V_1 - v$  when the rocket is advancing at velocity  $V_1$ . From the expression above, you can find the value of  $V_2$  as follows:

$$\bullet \quad V_2 = V_1 + \frac{mv}{M - 2m}$$

Substituting the value of  $V_2$  from that equation into this equation, we find the following:

$$V_2 = \frac{mv}{M - m} + \frac{mv}{M - 2m}$$

$$\bullet \quad V_2 = mv \left( \frac{1}{M - m} + \frac{1}{M - 2m} \right)$$

We've found the velocity of the rocket after discharging two small objects.

A real rocket will continue to discharge small objects—so let's derive a general expression for the rocket's velocity after discharging  $n$  small objects. Let's assume that the rocket continues to discharge small objects with mass  $m$  at relative velocity  $v$ .



As viewed from the rocket with velocity  $V_{n-1}$ , the small object is discharged at velocity  $-v$  to the rear of the rocket.

Assuming  $V_n$  for the velocity of the rocket when it discharges  $n$  small objects, the law of conservation of momentum is expressed as follows:

$$[M - (n - 1)m] V_{n-1} = (M - nm)V_n + m(V_{n-1} - v)$$

Thus,  $V_n$  is expressed as follows:

$$V_n = V_{n-1} + \frac{m}{M - nm} v$$

By using this expression repeatedly, you can find the following:

$$\textcircled{1} \quad V_n = \left( \frac{1}{M - m} + \dots + \frac{1}{M - nm} \right) mv = \sum_{i=1}^n \frac{m}{M - km} v$$

A real rocket continuously discharges exhaust from its rear engines, so we will transform expression  $\textcircled{1}$  for such a case. Assume that the rocket emits a jet of small mass  $\Delta m$  at one-minute intervals  $\Delta t$  at relative velocity  $-v$ . Assuming  $t$  for the time from the stationary state to the  $n$ th jet exhaust,  $t = n\Delta t$  is true. Assume  $V(t)$  is a function describing the rocket's velocity with respect to time, and transform expression  $\textcircled{1}$  into  $m \rightarrow \Delta m$ ,  $V_n \rightarrow V(t)$  to find the following:

$$\textcircled{2} \quad V(t) = \sum_{k=1}^n \frac{\Delta m}{M - (\Delta m / \Delta t) (k\Delta t)} v$$

At a point where the jet interval  $\Delta t$  is divided into infinitely small sections—that is, when  $\Delta t \rightarrow 0$ , you can find the sum using integral calculus.\* To work with integral calculus, note the following transformations:  $n$  becomes  $\infty$  and  $\Delta m / \Delta t$  becomes  $dm / dt$  (mass lost in

**WARNING:**  
**CALCULUS**  
**AHEAD!**



\* The expression  $\Delta t \rightarrow 0$  can be read aloud as "the change in time approaches zero."

unit time, or mass that is discharged in the form of fuel exhaust). Transform the equation as follows:  $\Delta m \rightarrow (dm / dt) dt$ . The following equation will result:

$$\textcircled{1} \quad V(t) = v \int_0^t \frac{1}{M - (dm / dt) t} \left( \frac{dm}{dt} \right) dt$$

$$= v \int_0^t \frac{1}{M (dm / dt)^{-1} - t} dt$$

If exhaust discharge in unit time is uniform, the following is true:

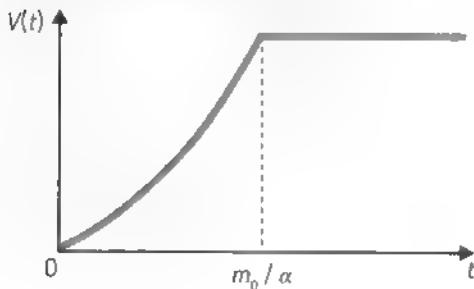
$$dm / dt = \alpha \quad (\text{a constant value})$$

This means that alpha ( $\alpha$ ) is a measure of how much mass the engine is discharging per unit time:

$$\textcircled{1} \quad V(t) = v \int_0^t \frac{1}{(M / \alpha) - t} dt = v [-\log_e (M / \alpha - t)]_0^t$$

$$= v \log_e \left( \frac{M}{M - \alpha t} \right)$$

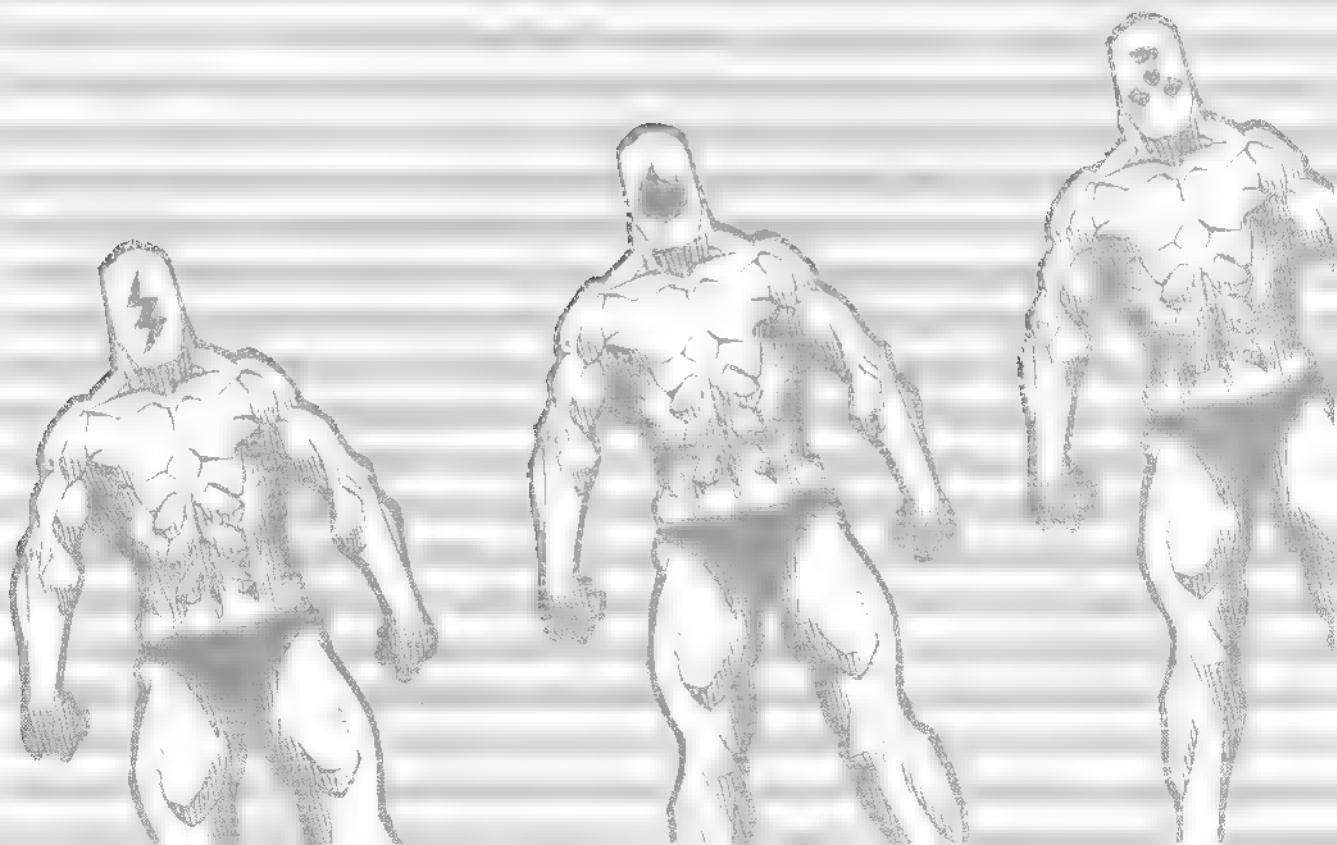
Expression  $\textcircled{1}$  represents the velocity of a rocket with initial velocity  $V(0) = 0$ . Note that  $\alpha t$  is the total mass of the exhaust emitted by the rocket in time interval  $t$ . Therefore, assuming that the initial total mass of fuel carried in the rocket is  $m_0$ , the rocket consumes all the fuel in time  $t$  ( $t = m_0 / \alpha$ ) and then shifts to uniform motion from accelerated motion (as shown in the following figure).





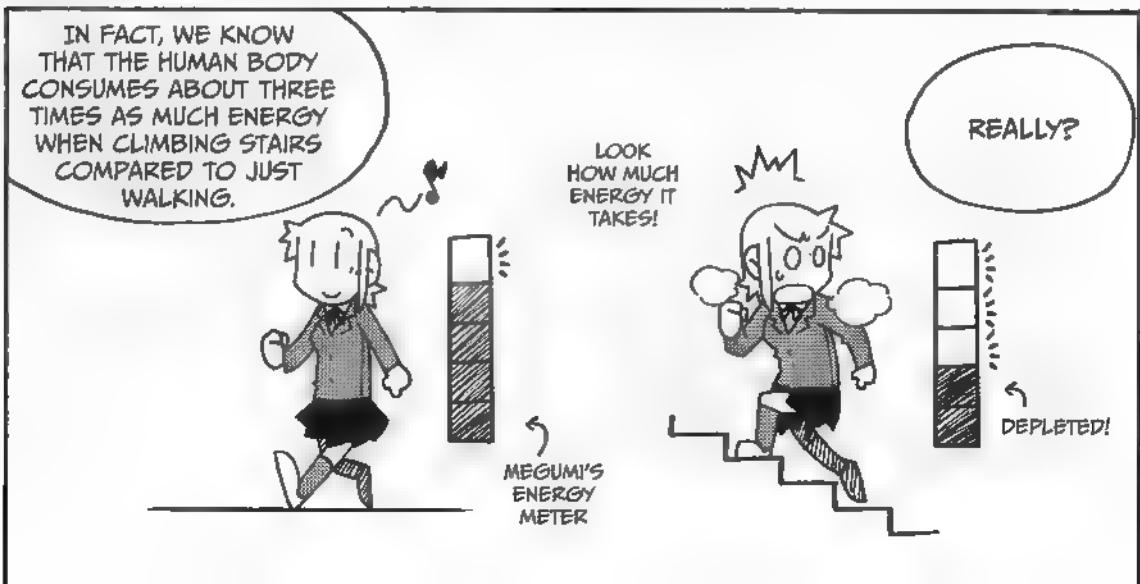
4

ENERGY



## WORK AND ENERGY





BUT WE SEE THE TERM ENERGY ALL OVER THE PLACE, DON'T WE?

YEAH!  
LIKE ENERGY-  
EFFICIENT CARS,  
GREEN ENERGY, AND  
ENERGY DRINKS!

ENERGY IS A WORD A LOT LIKE FORCE. PEOPLE USE THE TERM RATHER LOOSELY TO DESCRIBE THINGS, BUT...

WAIT!  
YOU MEAN...

ENERGY HAS A SPECIFIC MEANING IN PHYSICS?

YES.

JUST LIKE HOW FORCE IS DEFINED ACCORDING TO THE LAWS OF MOTION,

ENERGY ALSO HAS A STRICT DEFINITION.

GLUG  
GULP

THAT REMINDS  
ME—I'VE HEARD  
THE TERMS KINETIC  
ENERGY AND  
POTENTIAL ENERGY  
BEFORE.

AHHHH!

A MOVING OBJECT  
CONTAINS ENERGY  
THAT IS REFERRED TO  
AS KINETIC ENERGY.  
IT REPRESENTS  
THE ENERGY OF  
MOTION.

IT SOUNDS SIMILAR  
TO MOMENTUM. BUT  
KINETIC ENERGY  
MUST BE DIFFERENT,  
RIGHT?

WANT A  
DRINK?

Y...  
Y...  
Y...

YES, THEY ARE  
DIFFERENT. MOMENTUM  
IS GOVERNED BY THE  
LAW OF CONSERVATION  
OF MOMENTUM, BUT  
ENERGY MUST ALSO  
BE CONSERVED.

YOU MEAN THAT  
THERE'S A LAW  
DESCRIBING THE  
CONSERVATION OF  
ENERGY, TOO?



YES. ENERGY CAN  
TAKE MANY FORMS,  
THOUGH. THERE'S  
KINETIC ENERGY,

NUCLEAR  
ENERGY, AND  
MANY MORE.

POTENTIAL  
ENERGY, CHEMICAL  
ENERGY, THERMAL  
ENERGY,

DON'T YOU  
LIKE IT?

UH, ARE YOU  
OKAY?

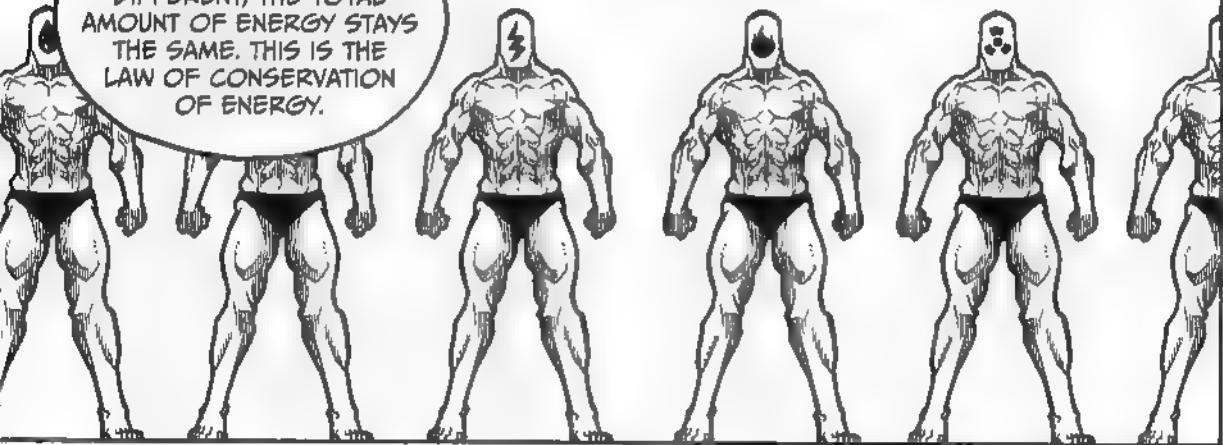
AHEM. ENERGY EXISTS IN MANY FORMS,

AND IT IS POSSIBLE TO TRANSFORM IT BETWEEN THESE FORMS.

SO ENERGY IS LIKE A SHAPE SHIFTER...

EVEN THOUGH THESE FORMS ARE VERY DIFFERENT, THE TOTAL AMOUNT OF ENERGY STAYS THE SAME. THIS IS THE LAW OF CONSERVATION OF ENERGY.

TOTAL AMOUNT OF ENERGY IS THE SAME

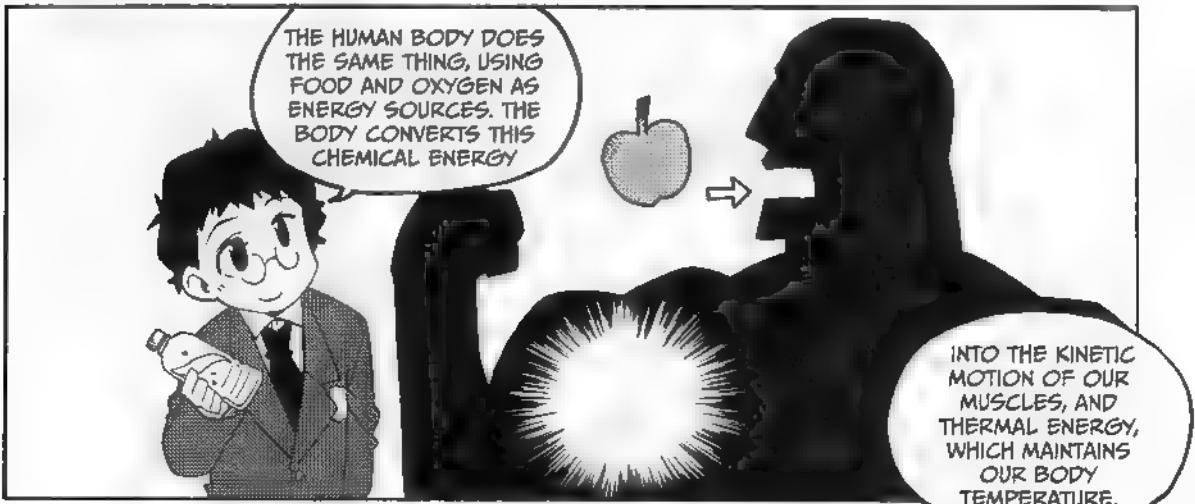
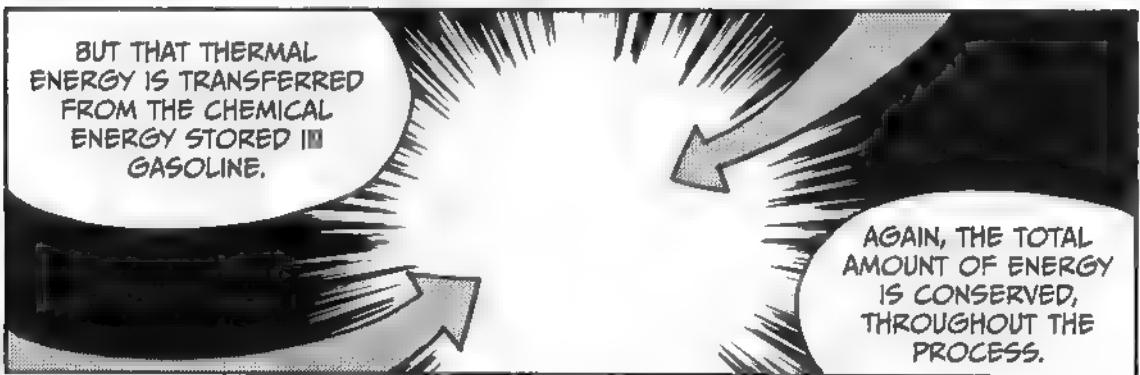
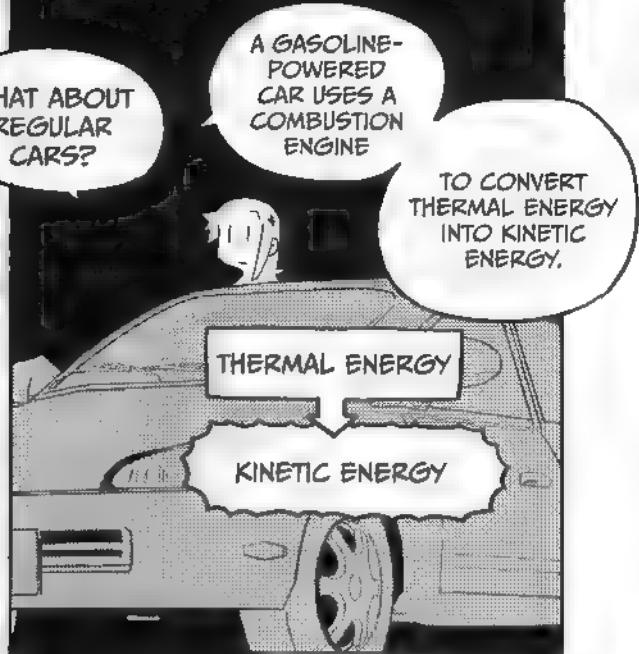
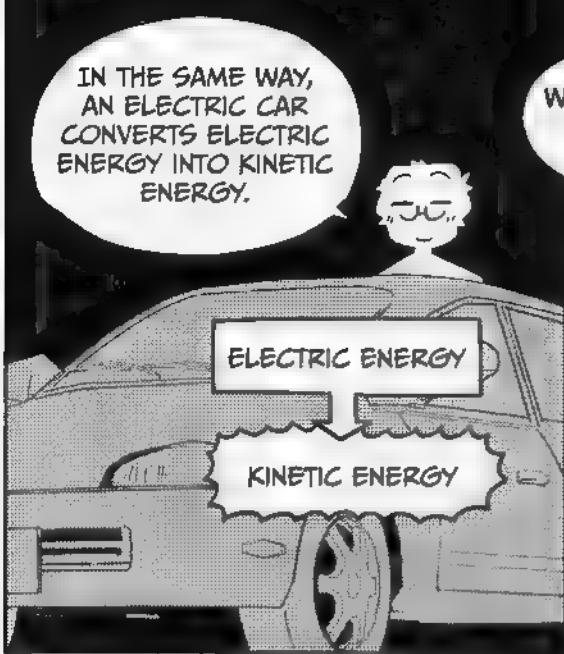


LET'S USE A REAL-LIFE EXAMPLE,

LIKE A HEADLIGHT ON A BICYCLE.

THE HEADLIGHT CONVERTS THE KINETIC ENERGY OF THE TURNING BICYCLE WHEEL INTO ELECTRICAL ENERGY AND THEN INTO LIGHT ENERGY.

OH, YEAH!  
I GET IT!



SO EVEN IN OUR BODIES, ENERGY IS CHANGING FORM.

BOY!

SO WHEN WE "CONSUME" ENERGY...

WE'RE REALLY JUST CHANGING IT INTO A DIFFERENT FORM.

ENERGY IS ALWAYS CIRCULATING, BUT THE TOTAL AMOUNT OF ENERGY REMAINS CONSTANT.

BUT LET'S GET A LITTLE LESS ABSTRACT AND DISCUSS

POTENTIAL ENERGY AND KINETIC ENERGY. THESE ARE BOTH KINDS OF MECHANICAL ENERGY.

OOOO



POTENTIAL ENERGY?

HMM...

WE'LL TALK ABOUT THAT LATER.

LET'S START WITH KINETIC ENERGY.

OKAY!!



THE ENERGY OF AN  
OBJECT IN MOTION  
CAN BE EXPRESSED  
AS FOLLOWS:



BUT  
WAIT!

KINETIC ENERGY =  $\frac{1}{2} \times \text{MASS} \times \text{SPEED} \times \text{SPEED}$

$$KE = \frac{1}{2}mv^2$$

YOU SAID SPEED,  
NOT VELOCITY!



GOOD POINT!

SINCE SPEED IS A QUANTITY  
WITH ONLY A MAGNITUDE,  
KINETIC ENERGY MUST  
ALSO BE A QUANTITY WITH  
ONLY A MAGNITUDE. WE'LL  
USE THE VARIABLE  $v$  FOR  
SIMPLICITY'S SAKE.

IT WILL NEVER BE  
NEGATIVE.

LET'S COMPARE  
KINETIC ENERGY  
TO MOMENTUM.

DO YOU  
REMEMBER THIS  
EQUATION?

MOMENTUM = MASS  $\times$  VELOCITY

$$p = mv$$

WHAT DO  
YOU MEAN?

OF COURSE!

MOMENTUM IS A VECTOR QUANTITY THAT HAS BOTH MAGNITUDE AND DIRECTION.

1.25

3.

RIGHT. ALSO, EVEN WHEN THE MOMENTUM OF ONE OBJECT IS EQUIVALENT TO THAT OF ANOTHER,

THEIR KINETIC ENERGY MAY NOT BE EQUAL!

I SEE-SO KINETIC ENERGY DOESN'T HAVE AN ORIENTATION.

OH, YEAH?

FOR EXAMPLE, COMPARE THE MOMENTUM OF AN OBJECT WITH A MASS OF 1 KG AND A VELOCITY OF 1 M/S WITH...

AN OBJECT WITH A MASS OF 0.5 KG AND A VELOCITY OF 2 M/S. THE TWO HAVE THE SAME MOMENTUM: 1 KG × M/S.

1 (m/s)

1 (kg)

$$p = 1 \text{ kg} \times \text{m/s}$$

$$\text{KE} = 0.5 \text{ J}$$

BUT, IN THE CASE OF KINETIC ENERGY, THE VALUE FOR THE FIRST BALL IS  $\frac{1}{2} \times 1 \text{ kg} \times (1 \text{ m/s})^2 = 0.5 \text{ J}$ . FOR THE SECOND BALL...

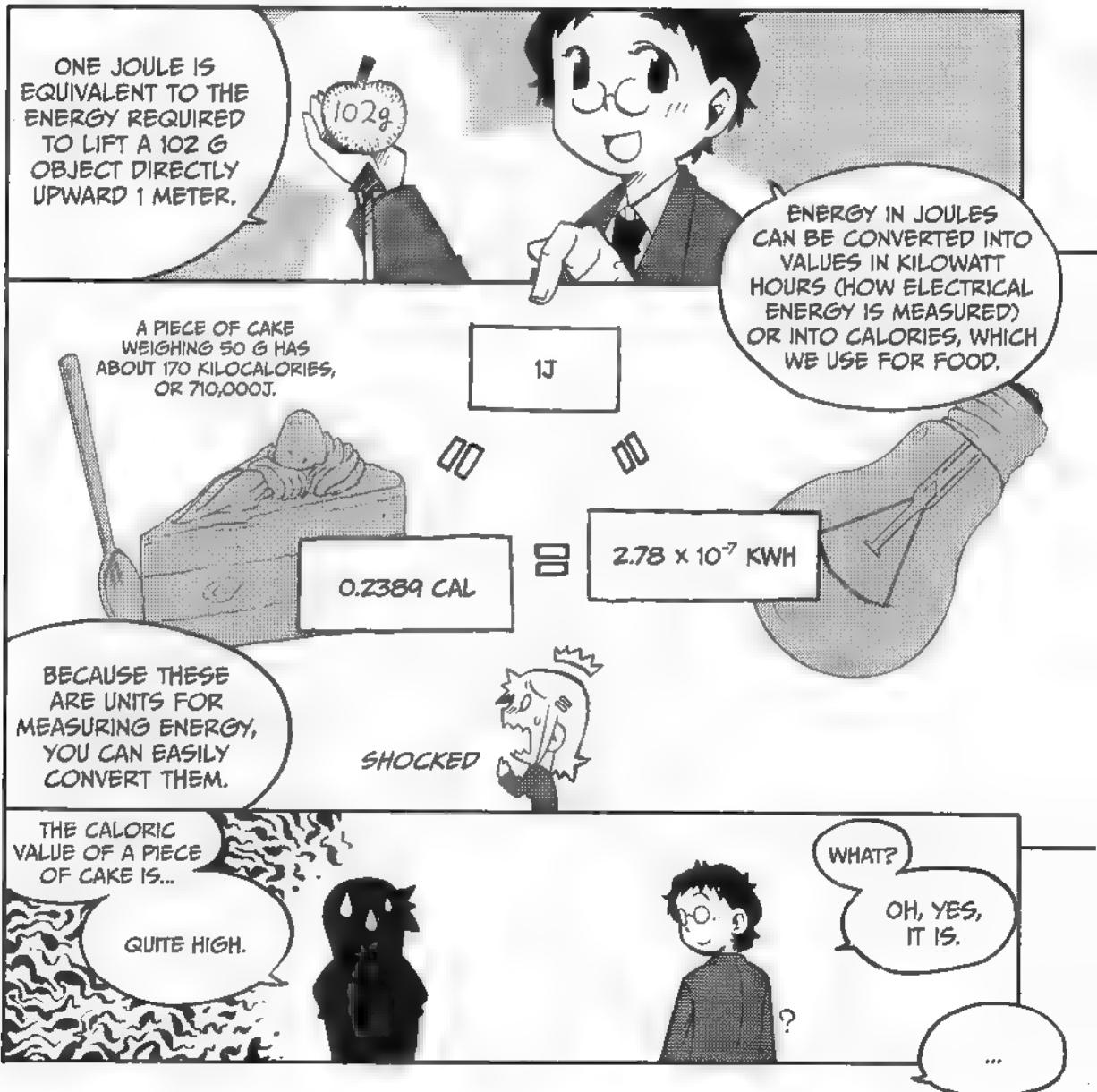
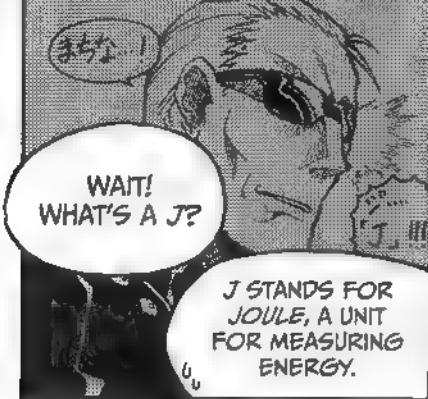
2 (m/s)

0.5 (kg)

$$p = 1 \text{ kg} \times \text{m/s}$$

$$\text{KE} = 1 \text{ J}$$

$$\text{ENERGY IS EQUAL TO } \frac{1}{2} \times 0.5 \text{ kg} \times (2 \text{ m/s})^2 = 1 \text{ J}$$



# LABORATORY

## WHAT'S THE DIFFERENCE BETWEEN MOMENTUM AND KINETIC ENERGY?



The difference between momentum and kinetic energy is easy to see when we consider two or more objects together.



Oh, yeah?



Let's recall the scenario where you were stranded outside your spaceship (page 126), and you used the law of conservation of momentum to return to the ship. Your momentum changed as a result of the momentum of the wrench, which you threw in the opposite direction. And, as I'm sure you recall, we use the equation  $p = mv$  to express the relationship between momentum, mass, and velocity.



Sure, I remember.



Before you threw the wrench, the momentum for both objects was zero (as  $v = 0$ ). After throwing the wrench, given the law of conservation of momentum, we know the following:

$$\begin{aligned} &\text{the sum of the momentum of the wrench and astronaut} \\ &= mv + MV = 0 \end{aligned}$$

Thus, we know that  $mv = -MV$ . In other words, the momentum of the wrench ( $mv$ ) and your momentum ( $MV$ ) are equivalent in magnitude and opposite in direction. They must equal zero when added together.



Since momentum is a vector, it has an orientation! So two momentums with equivalent magnitude and opposite directions will cancel each other out.



Now, let's think about the kinetic energy of the wrench and that of the astronaut. Before throwing the wrench, both are stationary, and the momentum is zero for both objects. After throwing the wrench, the sum of the energy of the two objects in motion is not zero:

$$KE_{\text{wrench}} + KE_{\text{astronaut}} = \frac{1}{2}mv^2 + \frac{1}{2}MV^2 > 0$$



But you said energy is always conserved!



This kinetic energy was generated when you threw the tool. Consider the law of conservation of energy—the amount of energy lost in your body should be the same as the amount of kinetic energy gained in these two objects.



Well, okay.



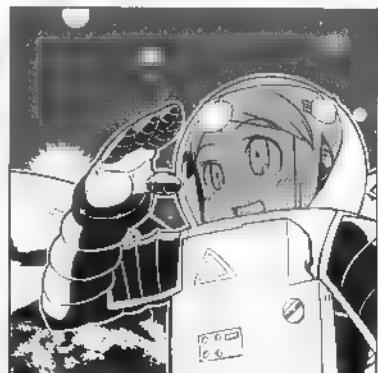
While it's difficult to accurately measure the energy expended by the human body, we can say that it's possible to determine a decrease of energy in the body by finding the energy transferred by that body.



In other words, I know that my body has lost at least as much energy as I have gained in the objects I've thrown, right?

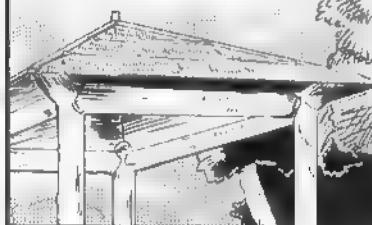


Yes, that's it. Now you need to remember, we must keep in mind the differences between energy and momentum.



## POTENTIAL ENERGY

EARLIER, I MENTIONED THAT MECHANICAL ENERGY INCLUDES KINETIC ENERGY AND POTENTIAL ENERGY.



YOU CAN THINK OF POTENTIAL ENERGY AS THE ENERGY OF POSITION.



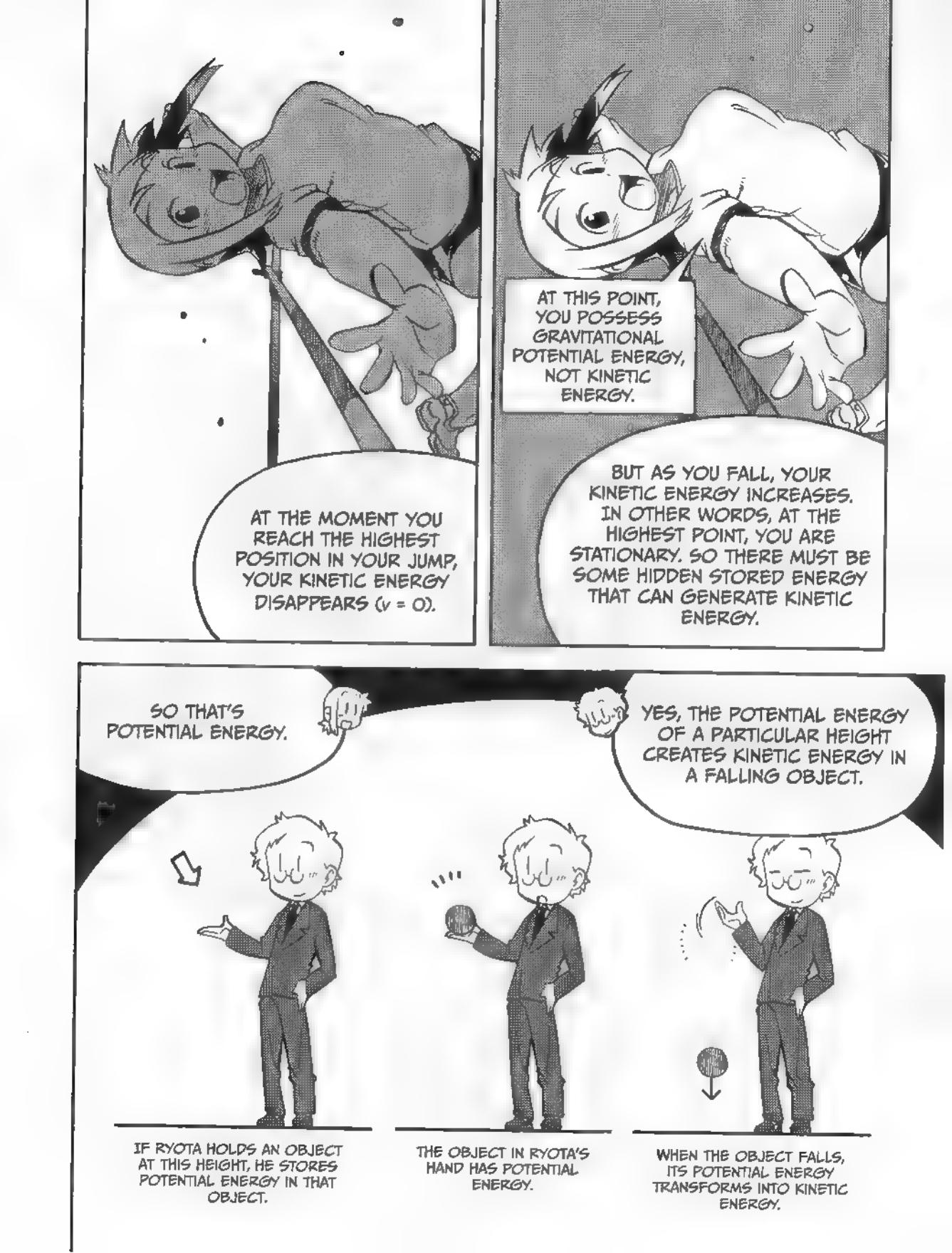
WELL,

POTENTIAL REFERS TO THE STORED ABILITY TO DO WORK.



SO DOES POTENTIAL ENERGY MEAN STORED ENERGY?

LET'S USE YOUR HIGH JUMP AS AN EXAMPLE.



AT THE MOMENT YOU REACH THE HIGHEST POSITION IN YOUR JUMP, YOUR KINETIC ENERGY DISAPPEARS ( $v = 0$ ).

AT THIS POINT, YOU POSSESS GRAVITATIONAL POTENTIAL ENERGY, NOT KINETIC ENERGY.

BUT AS YOU FALL, YOUR KINETIC ENERGY INCREASES. IN OTHER WORDS, AT THE HIGHEST POINT, YOU ARE STATIONARY. SO THERE MUST BE SOME HIDDEN STORED ENERGY THAT CAN GENERATE KINETIC ENERGY.

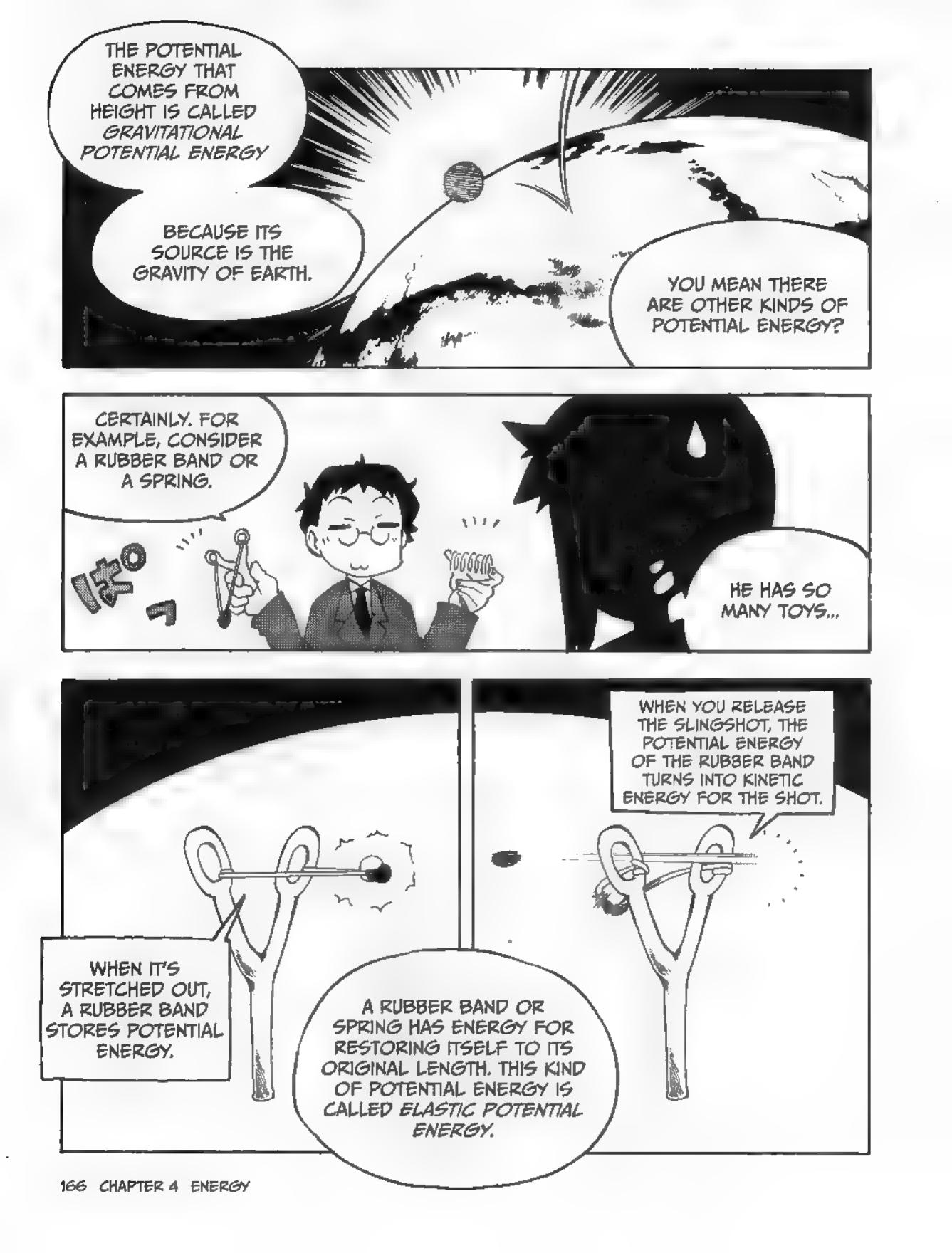
SO THAT'S POTENTIAL ENERGY.

YES, THE POTENTIAL ENERGY OF A PARTICULAR HEIGHT CREATES KINETIC ENERGY IN A FALLING OBJECT.

IF RYOTA HOLDS AN OBJECT AT THIS HEIGHT, HE STORES POTENTIAL ENERGY IN THAT OBJECT.

THE OBJECT IN RYOTA'S HAND HAS POTENTIAL ENERGY.

WHEN THE OBJECT FALLS, ITS POTENTIAL ENERGY TRANSFORMS INTO KINETIC ENERGY.



THE POTENTIAL ENERGY THAT COMES FROM HEIGHT IS CALLED GRAVITATIONAL POTENTIAL ENERGY

BECAUSE ITS SOURCE IS THE GRAVITY OF EARTH.

YOU MEAN THERE ARE OTHER KINDS OF POTENTIAL ENERGY?

CERTAINLY. FOR EXAMPLE, CONSIDER A RUBBER BAND OR A SPRING.

WHOO

...

...

HE HAS SO MANY TOYS...

WHEN IT'S STRETCHED OUT, A RUBBER BAND STORES POTENTIAL ENERGY.

A RUBBER BAND OR SPRING HAS ENERGY FOR RESTORING ITSELF TO ITS ORIGINAL LENGTH. THIS KIND OF POTENTIAL ENERGY IS CALLED ELASTIC POTENTIAL ENERGY.

WHEN YOU RELEASE THE SLINGSHOT, THE POTENTIAL ENERGY OF THE RUBBER BAND TURNS INTO KINETIC ENERGY FOR THE SHOT.

YOU MUST LIFT AN OBJECT OR PULL THE END OF A RUBBER BAND TO GIVE AN OBJECT POTENTIAL ENERGY.

IN THE SAME WAY, YOU MUST IMPOSE A FORCE ON AN OBJECT TO CREATE KINETIC ENERGY.

SPROINNNNG!

THUS, IN ORDER TO TRANSFORM ENERGY, YOU MUST IMPOSE A FORCE OVER A DISTANCE.

THIS IS REFERRED TO AS WORK.

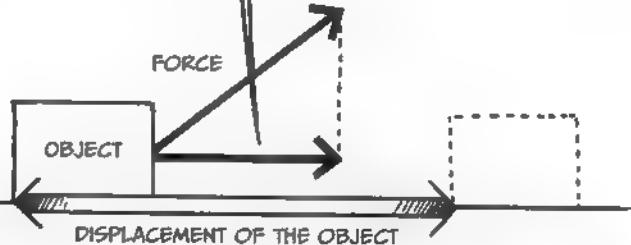
WELL, IT DOESN'T SEEM TO HAVE ANYTHING TO DO WITH BUSINESS CASUAL.

YOU'RE RIGHT. WORK IN MECHANICS IS DEFINED PRECISELY AS FOLLOWS:

WORK = DISPLACEMENT OF AN OBJECT  $\times$  THE COMPONENT OF FORCE APPLIED IN THE SAME DIRECTION

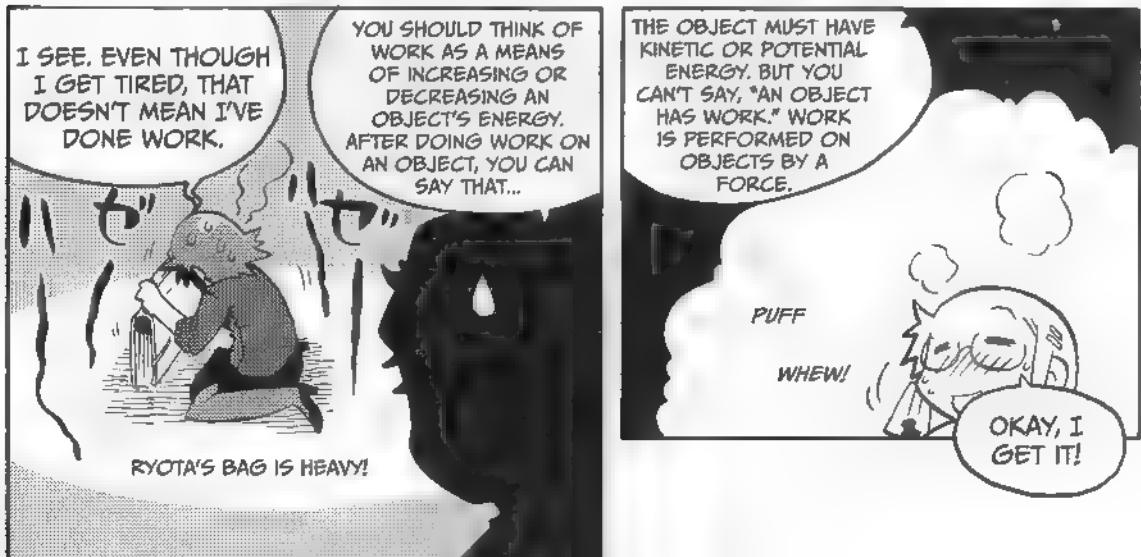
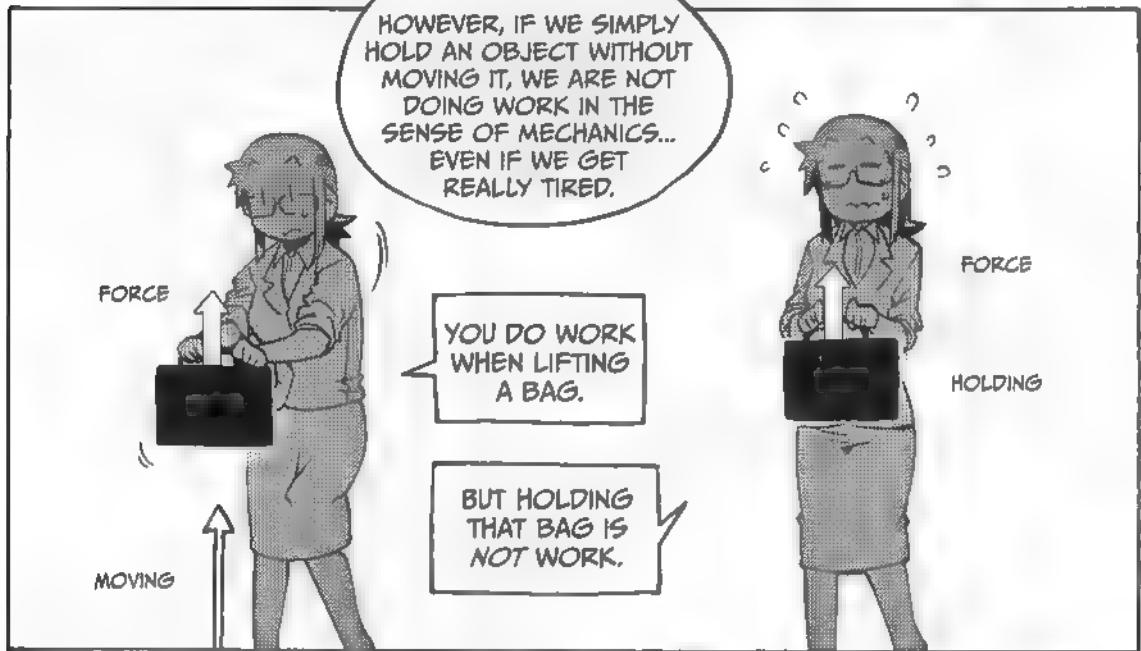
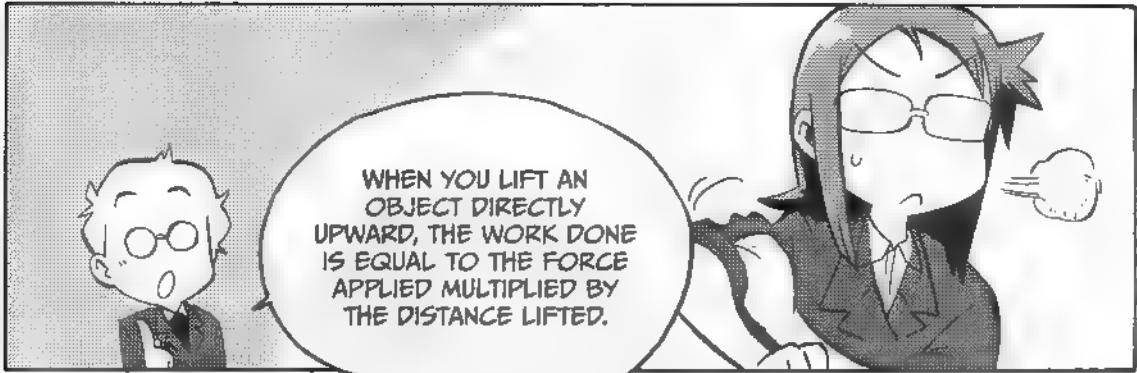
SEE?

COMPONENT OF FORCE APPLIED IN THE DIRECTION OF DISPLACEMENT



SIMPLY PUT, WORK IS EQUAL TO THE DISTANCE MULTIPLIED BY THE FORCE...

WELL, YES, BUT WE HAVE TO CONSIDER THE ORIENTATION OF THAT FORCE, TOO.



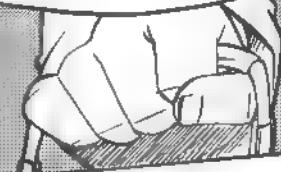
## WORK AND POTENTIAL ENERGY

SO, YOU CAN INCREASE POTENTIAL ENERGY BY DOING WORK.



YEAH, IF YOU DO WORK TO LIFT AN OBJECT, ITS POTENTIAL ENERGY INCREASES.

FOR EXAMPLE, LET'S CONSIDER THAT BAG AGAIN.



FORCE FROM THE HAND  
X  
HEIGHT THE OBJECT IS RAISED

HERE, WORK HAS BEEN DONE.

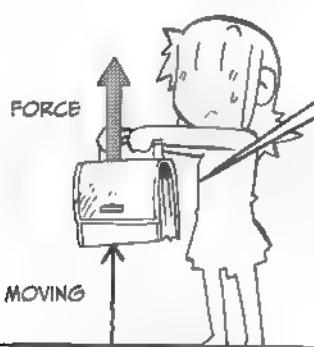
THE ORIENTATION OF THE FORCE AND THAT OF MOVING THE BAG RESULTS IN A POSITIVE VALUE FOR THE AMOUNT OF WORK.



THAT MEANS THE POTENTIAL ENERGY HAS INCREASED.

IS THE VALUE OF WORK NEGATIVE IF I LOWER THE BAG?

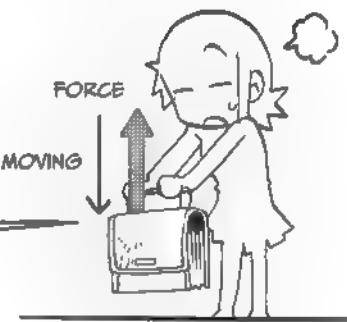
EXACTLY.



POTENTIAL ENERGY INCREASES

POTENTIAL ENERGY DECREASES

POSITIVE WORK

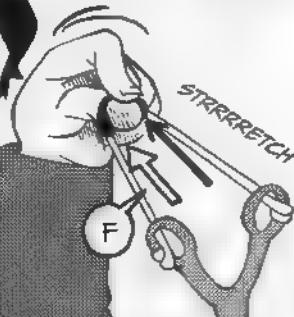


NEGATIVE WORK

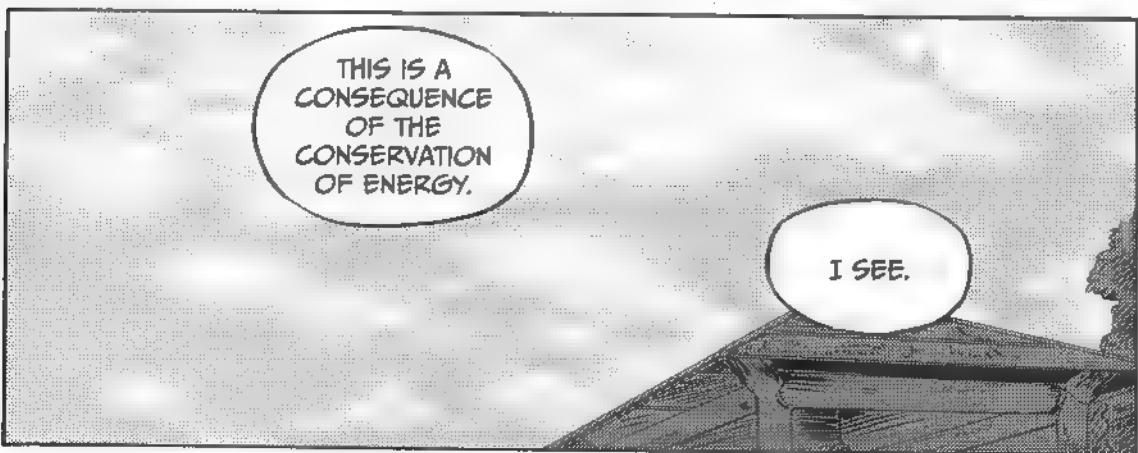
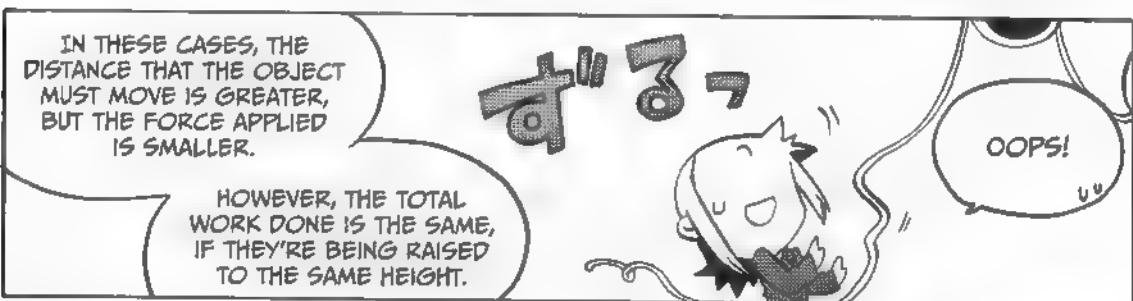
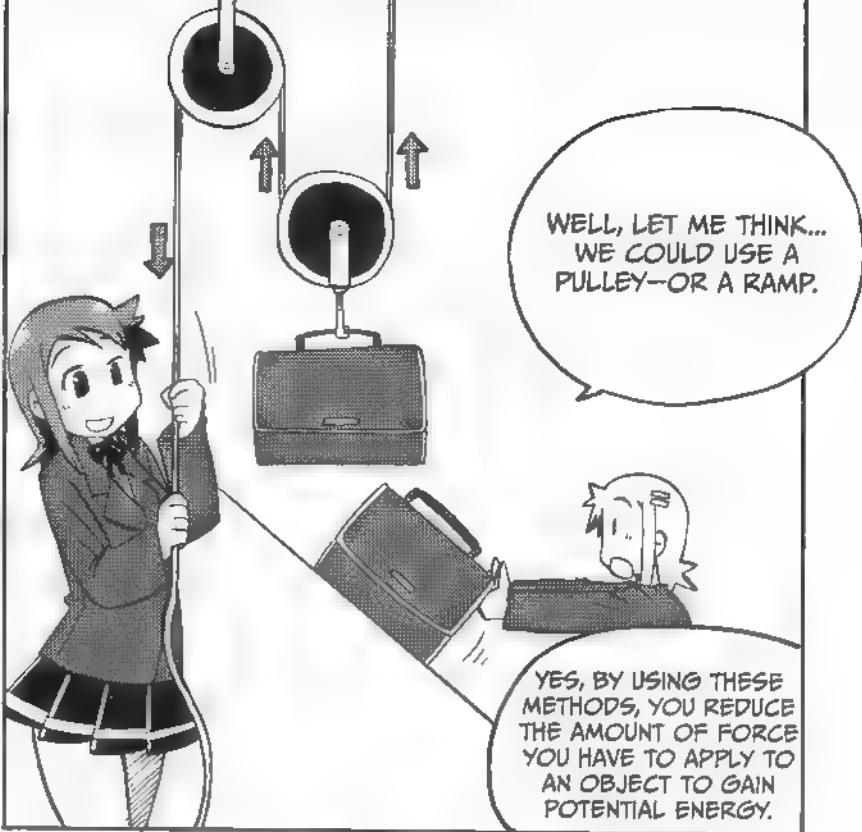
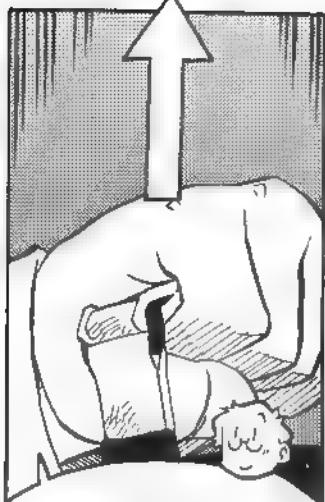
WHEN YOU DECREASE THE BAG'S POTENTIAL ENERGY, THE ORIENTATION OF THE FORCE IS OPPOSITE THE DIRECTION OF MOTION, MEANING THAT NEGATIVE WORK IS DONE ON THE BAG.



SIMILARLY, WHEN YOU PULL A RUBBER BAND, YOU ARE DOING POSITIVE WORK,



SINCE POTENTIAL ENERGY IS STORED.

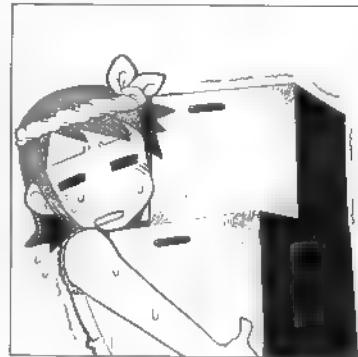
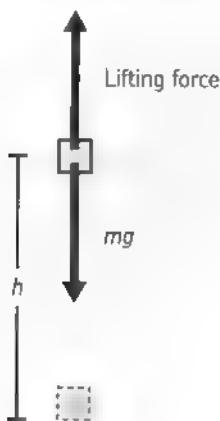


# LABORATORY

## WORK AND THE CONSERVATION OF ENERGY



Let's consider a scenario in which we are lifting a heavy load to a certain height. The simplest way to do this is to lift straight up. The following diagram shows how it looks.



We are lifting a load with mass  $m$  to height  $h$ .



Let's consider how much work we must do to lift the load to a height of  $h$  by imposing a force equal to the force of gravity of the mass—that is, we'll impose a force upward equivalent to the force downward from gravity. Assuming  $g$  for gravitational acceleration, we know that the force downward is  $mg$ :

$$\text{work upward} = \text{force of lifting} \times \text{height } h = mgh$$

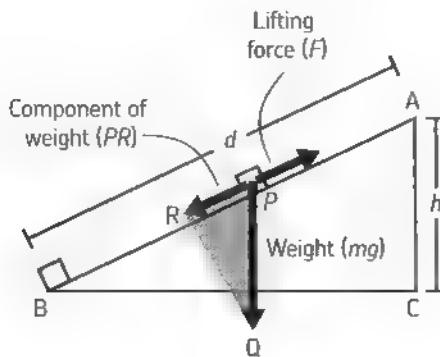
Note that for simplicity's sake, we won't take into account friction or air resistance in these examples. But this is a hard way to lift something so heavy!



Hmm . . . maybe it'd be easier if we pushed the load up a ramp.



Yes, let's consider the case of pushing the load up an incline.



Look at this diagram. The magnitude of the force needed to push the load up this ramp ( $F$ ) is equal to the component of the force of gravity parallel to the ramp ( $PR$ ). So, if the ramp has a length of  $d$ , the work required to move the load to height  $h$  can be represented as:

$$\text{work} = Fd$$

Now, you know intuitively that  $F$  is smaller than  $mg$ , and  $d$  is larger than  $h$ .



That makes sense. Is that why it takes the same amount of work to push the load up a ramp as it does to lift the load straight up?



Yes, indeed. Now let's show why this works, mathematically.  $\triangle ABC$  represents the ramp in the figure, and  $\triangle PQR$  represents the composition of the force  $mg$ . These two triangles are similar—this means that  $\angle CAB = \angle RPQ$ . This also means that the proportion of their corresponding sides must be the same, as well. Thus, the following must be true:

$$\frac{AB}{AC} = \frac{PQ}{PR}$$

Let's make this a little less abstract. The line segment  $AB$  equals  $d$  (length of ramp) and  $AC$  equals  $h$  (height). Similarly, the line segment  $PQ$  equals  $mg$  (the force downward, due to gravity), while  $PR$  equals  $F$  (the force applied to offset a portion of that force).



That means:

$$\frac{d}{h} = \frac{mg}{F}$$

Look, with just a little rearranging of this equation we get the following:

$$Fd = mgh$$

Therefore, the work to lift a load using a ramp must be equal to the work to lift that load straight upward.

Also, please note that our results are the same, regardless of the angle of the ramp. Given the conservation of energy, regardless of the lifting route, the work done for lifting an object with mass  $m$  to height  $h$  is equal to the following:

$$\text{force required to balance gravity} \times \text{height} = mgh$$



So, whatever method you use to lift something, the amount of work you do is the same.



To put it another way, your work increases the potential energy of the load by  $mgh$ .



And I bet it works for negative work, too. That is, you'd see a decrease in potential energy of  $mgh$  if you lower an object by  $mgh$ .



Yep, that's right.

## WORK AND ENERGY

WHAT'S  
HAPPENING?  
I FEEL  
LIKE I'M  
SHRINKING...

WORK ISN'T  
ONLY DONE WHEN  
INCREASING OR  
DECREASING  
POTENTIAL  
ENERGY.

WORK CAN  
ALSO AFFECT THE  
KINETIC ENERGY  
OF AN OBJECT!

WHAT THE...?

I'M ALL  
GROWN  
UP!

YOU MEAN WORK IS  
ALSO DONE WHEN  
WE MOVE AN OBJECT  
OR BRING A MOVING  
OBJECT TO A HALT?



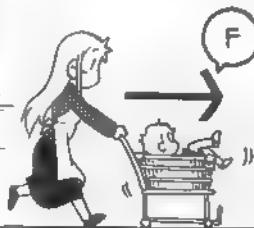
ARE YOU STILL  
LISTENING TO ME,  
NINOMIYA-SAN?

YES, GO ON  
WITH THE  
LESSON.

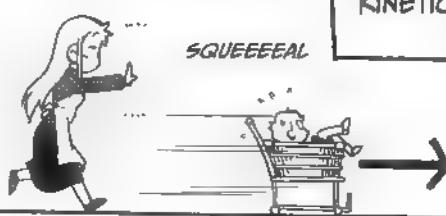
WELL.

AHEM.

WHILE YOU IMPOSE A  
FORCE FOR A GIVEN  
DISTANCE ON AN OBJECT  
AT REST, THAT OBJECT'S  
KINETIC ENERGY  
INCREASES.



IMPOSING A  
FORCE ON AN  
OBJECT



GENERATES  
KINETIC ENERGY.

WHOA. THIS IS TRUE FOR OBJECTS IN MOTION AS WELL. IN OTHER WORDS, THE KINETIC ENERGY OF AN OBJECT INCREASES EVEN MORE

IF YOU IMPOSE A FORCE IN THE DIRECTION OF THE OBJECT'S MOTION.

FOR SOME REASON, YOU REMIND ME OF A PACHINKO BALL.

SINCE ENERGY IS CONSERVED, WE KNOW THE FOLLOWING:

WORK DONE ON THE OBJECT = CHANGE IN THE OBJECT'S KINETIC ENERGY

THIS RELATIONSHIP MUST HOLD TRUE.

AH, YES.

IF THE FORCE WE IMPOSE ON AN OBJECT IS IN THE DIRECTION OF THE OBJECT'S MOTION—

THAT IS, WHEN THE FORCE AND VELOCITY ARE PARALLEL—WE WILL DO POSITIVE WORK.

WE KNOW THAT THERE'S BEEN A POSITIVE CHANGE IN KINETIC ENERGY—THAT IS, THE OBJECT IS SPEEDING UP.

I WANT SOME POCKY, MOMMY!

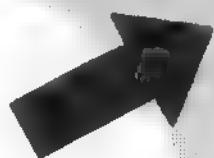


LIKEWISE, YOU CAN STOP AN OBJECT IN MOTION BY IMPOSING A FORCE IN A DIRECTION OPPOSITE TO ITS VELOCITY.

REDUCING ITS KINETIC ENERGY, I SUPPOSE.



AT THIS TIME, THE ORIENTATION OF VELOCITY AND THE FORCE ARE OPPOSED TO EACH OTHER, SO THE VALUE OF WORK WILL BE NEGATIVE.



THEREFORE, THE CHANGE IN KINETIC ENERGY ALSO TAKES A NEGATIVE VALUE—IT DECREASES.

THAT WAS BIZARRE.  
I'M GLAD I'M BACK TO MY OLD SELF AGAIN.

WHEW!

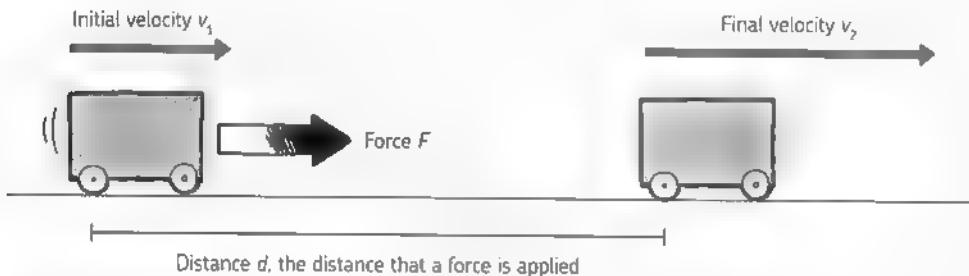


# LABORATORY

## THE RELATIONSHIP BETWEEN WORK AND KINETIC ENERGY



Let's examine how we can derive an equation that expresses the relationship between work and kinetic energy. Suppose we continue to impose force  $F$  on a cart in motion, in a direction parallel to that cart's velocity. That cart has mass  $m$  and starts with an initial, uniform velocity of  $v$ .



That means an additional force is imposed on the object in motion.



At this time, the following is true:

$$\text{work done on the object} = Fd$$

Also, since we've represented the final velocity as  $v_2$ , we can represent the change in the object's kinetic energy as the following:

$$\text{change in kinetic energy} = \frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2$$

And since we already know that the change in kinetic energy is equal to the work done on the object, we can express the following relationship:

$$\frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2 = Fd$$



Aha.



We can also derive this equation another way. Since  $F$  is defined as constant, the cart is experiencing uniform acceleration. Therefore, if we represent the cart's acceleration with  $a$ , we know that the following must be true:

$$v_2^2 - v_1^2 = 2ad$$

(Why is this so? See expression ❸ on page 85.) To get closer to our original expression, we'll substitute using Newton's second law:

$$F = ma, \text{ or rearranged just a little, } a = \frac{F}{m}$$

And we'll get the following:

$$v_2^2 - v_1^2 = \frac{2Fd}{m}$$

Then if you simply multiply both sides by  $\frac{1}{2}$ , you're there!

$$\frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2 = Fd$$



I can get it right if I calculate very carefully.

## BRAKING DISTANCE AND SPEED

USING WHAT WE KNOW ABOUT THE RELATIONSHIP BETWEEN KINETIC ENERGY AND WORK, LET'S CONSIDER A CAR'S BRAKING DISTANCE.

WHAT DO YOU MEAN, EXACTLY?

WELL, I GUESS IT'S NOT JUST FOR CARS. IT'S THE DISTANCE THAT ANY OBJECT IN MOTION REQUIRES TO STOP,

GIVEN A CERTAIN FORCE IN THE OPPOSITE DIRECTION.

GIVEN THAT WE KNOW A CHANGE IN KINETIC ENERGY IS EQUAL TO THE WORK PERFORMED, WE KNOW THAT THE FOLLOWING MUST BE TRUE OF BRINGING AN OBJECT IN MOTION TO REST:

$\frac{1}{2} \text{MASS} \times \text{SPEED}^2 = \text{FORCE OF THE BRAKES} \times \text{DISTANCE THE BRAKES ARE APPLIED}$

$$\frac{1}{2}mv^2 = F_{\text{brakes}} \times d$$

IF WE REARRANGE THE EQUATION, WE CAN SOLVE FOR THE BRAKING DISTANCE!



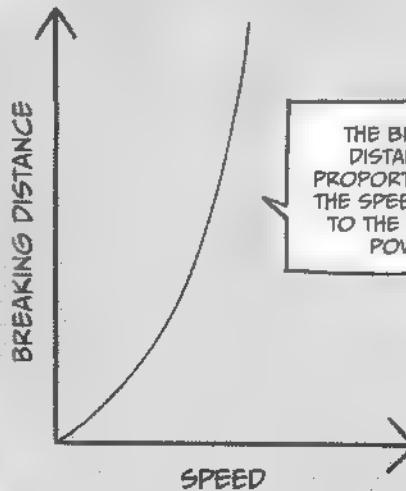
THIS EQUATION MEANS THAT THE GREATER THE MASS ( $m$ ) AND THE SPEED ( $v$ ) OF THE VEHICLE BECOME, THE GREATER THE REQUIRED DISTANCE TO BREAK ( $d$ ).

AND THE LARGER THE FORCE OF THE BRAKES ( $F_{\text{brakes}}$ ), THE SHORTER THE DISTANCE REQUIRED TO COME TO A COMPLETE STOP.

BUT WE'VE MULTIPLIED THE SPEED BY ITSELF!?

THAT MEANS THAT THE BRAKING DISTANCE ( $d$ ) IS PROPORTIONAL TO THE SPEED RAISED TO THE SECOND POWER.

WHEN THE INITIAL SPEED IS DOUBLED... DOES THAT MEAN THE BRAKING DISTANCE IS QUADRUPLED?



AHA, THAT IS EXCELLENT INSIGHT INTO THEIR RELATIONSHIP. IT IS DANGEROUS TO ASSUME THAT THE BRAKING DISTANCE IS LINEARLY PROPORTIONAL TO A CAR'S SPEED.



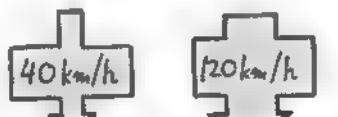
YEAH, DEFINITELY.

THE BRAKING DISTANCE IS IN FACT QUADRUPLED WHEN YOUR SPEED IS DOUBLED.



FOR A BICYCLE, IT'S NOT SUCH A BIG DEAL, BUT FOR AUTOMOBILES, IT CAN HAVE SERIOUS CONSEQUENCES.

FOR EXAMPLE, SUPPOSE A CAR IS TRAVELING AT 40 KM/H, AND ITS BRAKING DISTANCE IS 10 M. IF THIS SAME CAR IS TRAVELING AT 120 KM/H, OR AT A VELOCITY THREE TIMES HIGHER, WHAT IS THE BRAKING DISTANCE?



90m

UMMM... SINCE THE SPEED IS THREE TIMES HIGHER, WE JUST HAVE TO SQUARE THAT. SO  $3 \times 3 = 9$  TIMES GREATER, OR  $10 \text{ m} \times 9 = 90 \text{ m}$ .



SAFE DRIVERS  
WOULD DO WELL  
TO KEEP THIS  
PRINCIPLE IN MIND.

VRRRRRROOM



YOU'D  
BETTER  
START  
BRAKING  
NOW!

IF WE MISTAKENLY ASSUMED  
THAT OUR STOPPING DISTANCE  
WAS LINEARLY RELATED TO  
SPEED, WE'D THINK IT WAS  
ONLY 30 M. WE'D BE OFF  
BY 60 M!

DON'T  
WORRY,  
I STILL  
HAVE TIME!

DESPITE THIS DRIVER'S  
CONFIDENCE, A GRISLY  
ACCIDENT IS VERY  
POSSIBLE, SINCE THE  
BRAKING DISTANCE IS  
SO LARGE.

I HEAR THAT ALL  
THE BEST DRIVING  
SCHOOLS TEACH THAT  
THE BRAKING DISTANCE  
IS PROPORTIONAL  
TO THE VELOCITY  
SQUARED.

OH, I'M  
SURE.

YIKES!

## THE CONSERVATION OF MECHANICAL ENERGY

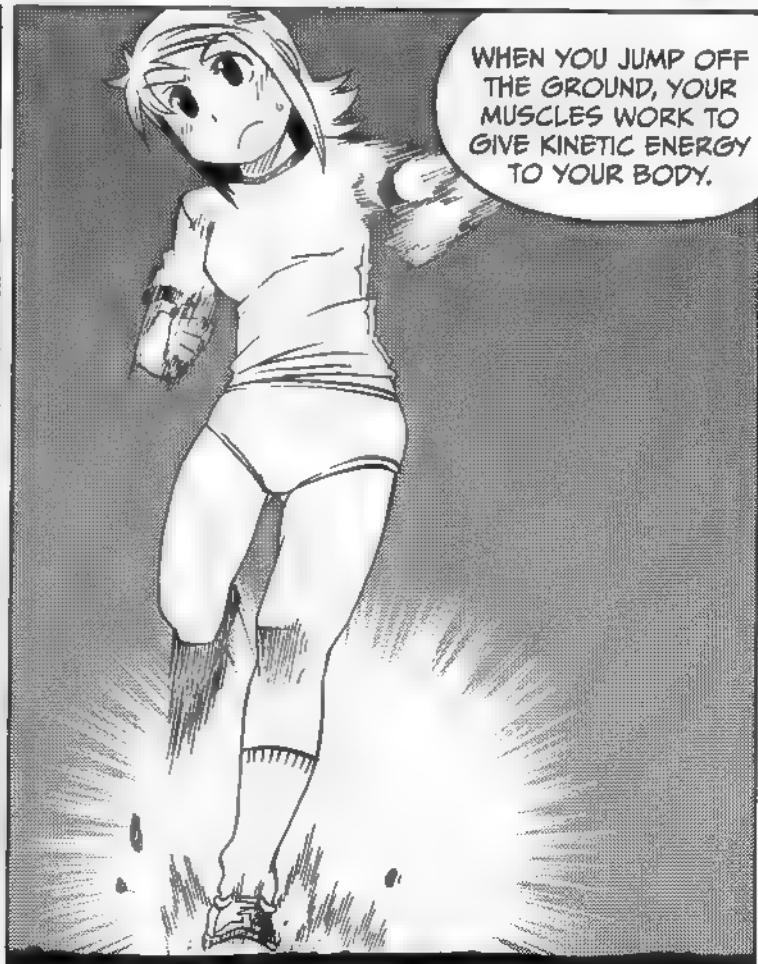
### TRANSFORMING ENERGY

SO, NOW WE KNOW HOW KINETIC ENERGY AND POTENTIAL ENERGY CAN BE TRANSFORMED INTO EACH OTHER.

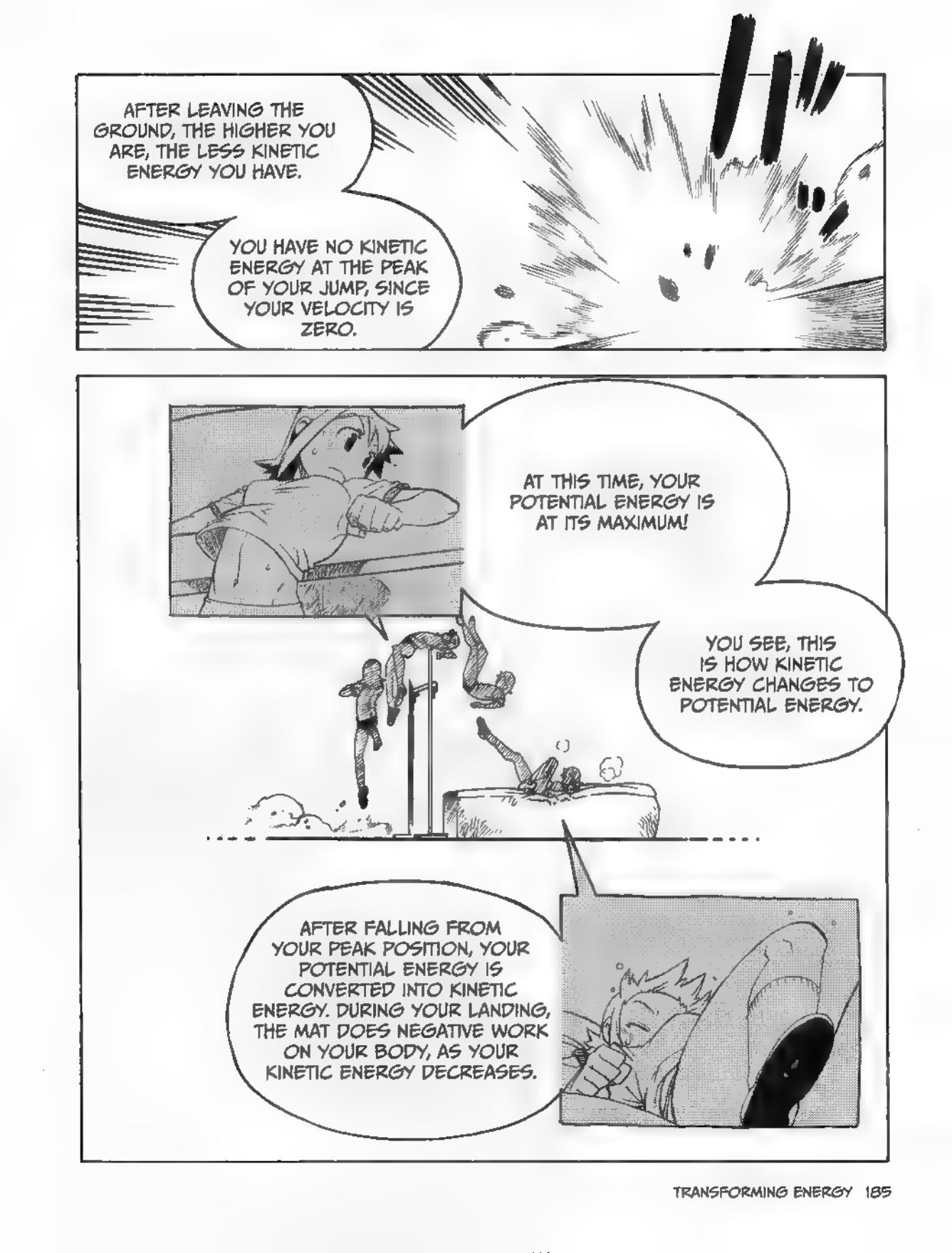
YES—  
ENERGY MUST BE  
CONSERVED, JUST  
LIKE MOMENTUM.



LET'S RECONFIRM THAT LAW USING THE EXAMPLE OF YOUR HIGH JUMP.



WHEN YOU JUMP OFF THE GROUND, YOUR MUSCLES WORK TO GIVE KINETIC ENERGY TO YOUR BODY.



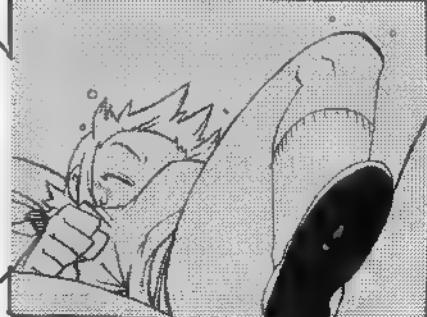
AFTER LEAVING THE GROUND, THE HIGHER YOU ARE, THE LESS KINETIC ENERGY YOU HAVE.

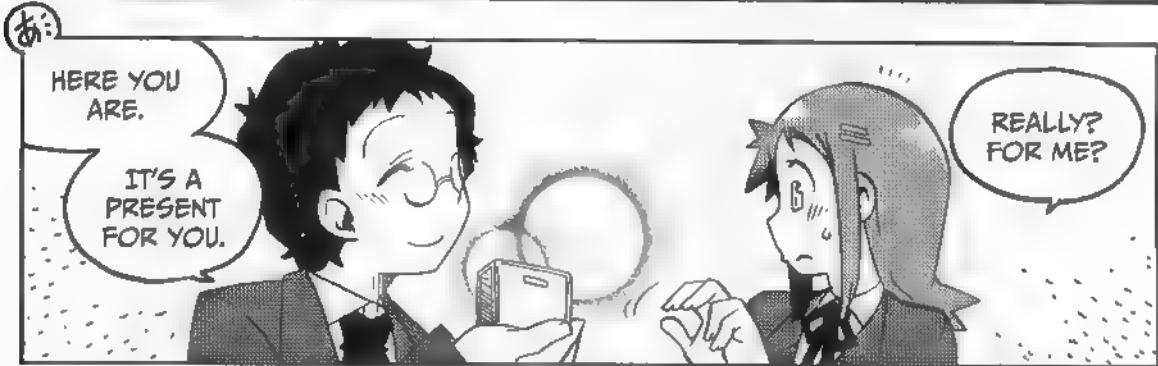
YOU HAVE NO KINETIC ENERGY AT THE PEAK OF YOUR JUMP, SINCE YOUR VELOCITY IS ZERO.

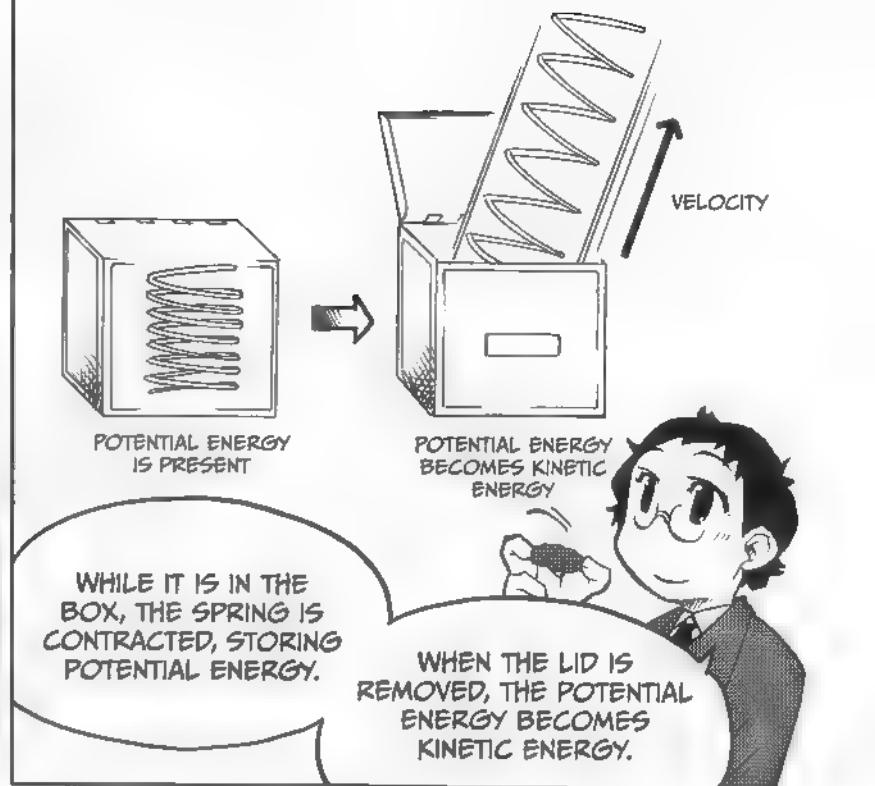
AT THIS TIME, YOUR POTENTIAL ENERGY IS AT ITS MAXIMUM!

YOU SEE, THIS IS HOW KINETIC ENERGY CHANGES TO POTENTIAL ENERGY.

AFTER FALLING FROM YOUR PEAK POSITION, YOUR POTENTIAL ENERGY IS CONVERTED INTO KINETIC ENERGY. DURING YOUR LANDING, THE MAT DOES NEGATIVE WORK ON YOUR BODY, AS YOUR KINETIC ENERGY DECREASES.

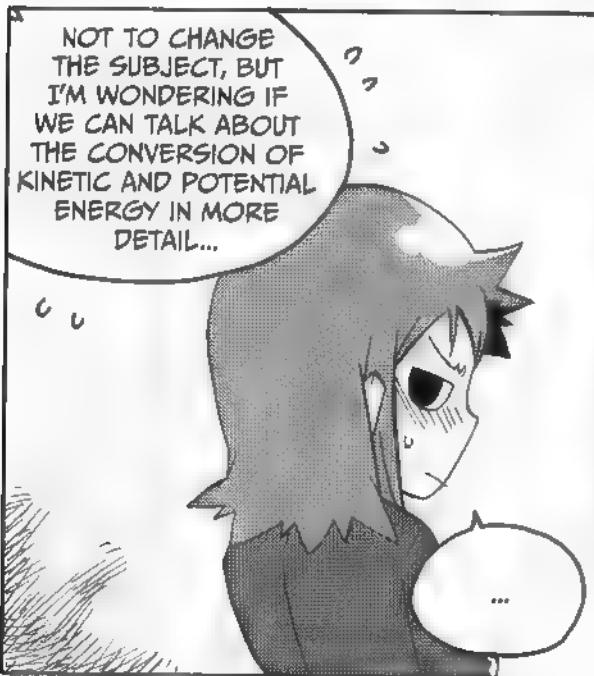






CONSERVATION OF MECHANICAL ENERGY

BOY, I NEVER THOUGHT THAT AN ATHLETE LIKE YOU WOULD BE...



WHEN A BALL IS THROWN STRAIGHT UPWARD, THE HIGHER IT GOES, THE MORE POTENTIAL ENERGY IT GAINS.

AND OF COURSE, IT LOSES KINETIC ENERGY IN THE SAME WAY.

JUST LIKE ME AND MY HIGH JUMP.

AT THE PEAK, ALL KINETIC ENERGY HAS BEEN CHANGED INTO POTENTIAL ENERGY.

AS THE BALL COMES DOWN, THAT POTENTIAL ENERGY IS CONVERTED INTO KINETIC ENERGY.

WHEREVER THE BALL IS, THE SUM OF THESE TWO FORMS OF ENERGY IS CONSTANT.

IT IS REFERRED TO AS THE LAW OF CONSERVATION OF MECHANICAL ENERGY.\*

POTENTIAL ENERGY

KINETIC ENERGY

HEIGHT  
4 m (PEAK)

3 m

2 m

1 m

0 m

MECHANICAL ENERGY

100%

75%

25%

50%

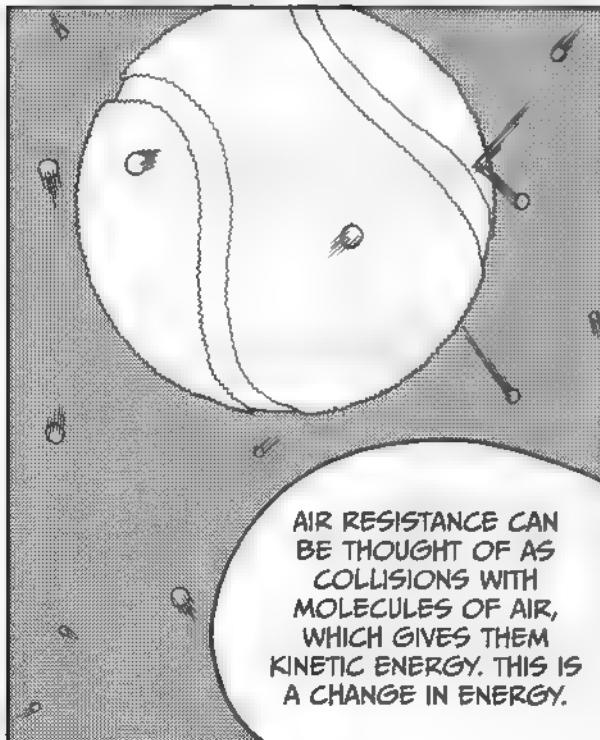
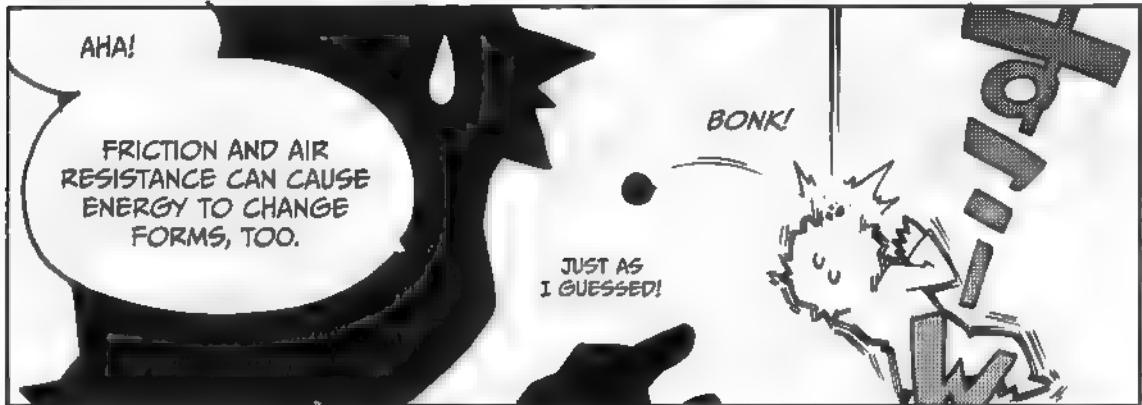
50%

25%

75%

100 %

\* THIS IS SIMPLY AN APPLICATION OF THE LAW OF CONSERVATION OF ENERGY!



# LABORATORY

## THE LAW OF CONSERVATION OF MECHANICAL ENERGY IN ACTION



Let's prove that the law of conservation of mechanical energy applies when throwing a ball straight upward.

First, we know that the equation for a change in kinetic energy and work is as follows:

$$\bullet \quad \frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2 = Fd$$

That is:

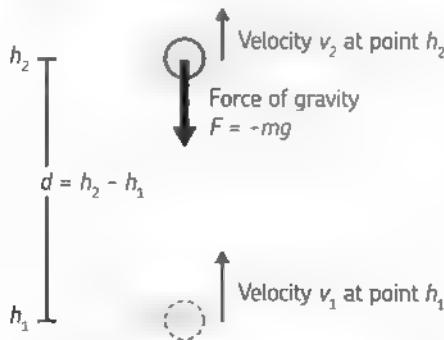
the change in *KE* = work



Yes, we confirmed that earlier.



In this case, the work *Fd* represents the work done by gravity. Assume that the ball starts at height  $h_1$  with velocity  $v_1$ . After traveling distance  $d$ , it is at height  $h_2$ , and its velocity has diminished to  $v_2$ . The distance  $d$  can be thought of as the change in height—or  $h_2 - h_1$ .



Yeah, so what's the big deal? Are you trying to show that the force of gravity is doing negative work on the ball?



Exactly. The force of gravity is acting against the direction of the velocity. So it's expressed as:

$$F = -mg$$

That means that the work done by the ball (force = distance) is equal to:

$$Fd = -mg(h_2 - h_1)$$

Substituting values from the first equation ①, we get the following:

$$\frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2 = -mg(h_2 - h_1)$$

Now, let's rewrite it a few times, first expanding the terms on the left side:

$$\frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2 = mgh_1 - mgh_2$$

Then, make a little switcheroo, and we have something that should be familiar:

$$\frac{1}{2}mv_2^2 + mgh_2 = \frac{1}{2}mv_1^2 + mgh_1$$



Yes, it is. It's showing that the sum of the kinetic energy and potential energy at both  $h_1$  and  $h_2$  must be the same.



Yes, that's it exactly.



So the left side of this equation is the total mechanical energy at point  $h_2$ , and the right side is the total mechanical energy at point  $h_1$ .



Yes, we've derived an equation that indicates that the sum of the mechanical energy must be equal at any two points of a ball's path, when it is thrown directly into the air.



Yes, I see that.



Now, let's use this equation to calculate something a bit different—the velocity ( $v_1$ ) at which you need to throw a ball to reach a certain *maximum* height ( $h_2$ ). Since the ball's velocity reaches zero at the peak, we know it has no kinetic energy at that time.

And for simplicity's sake, let's set  $h_1$  equal to 0—that is, we'll measure  $h_2$  from the ball's launching point. That is,  $h_2$  will equal  $d$ , the distance the ball travels.

This means that the kinetic energy the ball has at its launching point must equal the potential energy it has at its height.

Therefore, the following is true:

$$PE_2 = KE_1$$

$$mgd = \frac{1}{2}mv_1^2$$



Wait, I think I see something interesting here—mass appears on both sides of this equation. That means that the mass does not affect the relationship!



You're right! Let's solve for the initial velocity  $v_1$ :

$$mgd = \frac{1}{2}mv_1^2$$

$$gd = \frac{1}{2}v_1^2$$

$$2gd = v_1^2$$

$$\sqrt{2gd} = v_1$$



If we just use real numbers in this equation, we can find the required initial velocity to reach a particular height!



## FINDING THE SPEED AND HEIGHT OF A THROWN BALL

NOW LET'S APPLY THE EQUATION WE JUST DERIVED

TO FIND THE SPEED AT WHICH A BALL MUST BE THROWN TO REACH A HEIGHT OF 4 M.

LET'S ASSUME THAT WE ARE THROWING IT FROM A REFERENCE POINT OF 0 M,

SO THAT  $h_2 = d$ , AS WE DID BEFORE.

$$v_1 = \sqrt{2gd}$$

AND WE KNOW THAT  $g = 9.8 \text{ m/s}^2$  AND  $d = 4 \text{ m}$ .

LET ME SEE...

$$v_1 = \sqrt{2gd}$$

$$v_1 = \sqrt{2 \times 9.8 \text{ m/s}^2 \times 4 \text{ m}}$$

$$v_1 = 8.9 \text{ m/s!}$$

IS THAT RIGHT?

YEP, PERFECT!

CONVERTING THAT TO KILOMETERS PER HOUR, YOU GET  $8.9 \text{ m/s} \times 3600 \text{ s/h} \times 1 \text{ km} / 1000 \text{ m} = 32 \text{ km/h}$ .

AHA!

USING THIS EXPRESSION, MAYBE WE CAN CALCULATE HOW HIGH A BALL WOULD GO WITH AN INITIAL VELOCITY OF 100 KM/H...

YES, LET'S SEE... WE KNOW  $d = v_1^2 / 2g$

SO IT WILL REACH A HEIGHT OF ABOUT 39 M.

WOW.

YOU'RE SO FAST! JUST LIKE A PHYSICS OLYMPIAN.

# LABORATORY

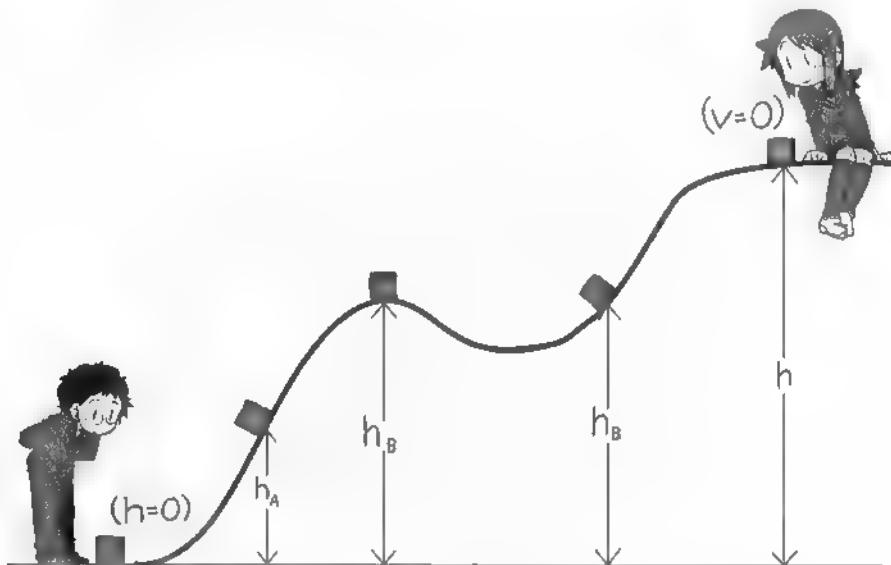
## CONSERVATION OF MECHANICAL ENERGY ON A SLOPE



The law of conservation of mechanical energy holds true, even when you're not talking about balls in the air, right? Wouldn't it work for lots of other situations, too, like an object on a slope?



Well, let's examine a case where you slide a box from height  $h$  to height 0. On the way down, let's assume that the box attains velocity  $v_A$  at height  $h_A$ , velocity  $v_B$  at height  $h_B$ , and so on.



Since  $v = 0$  at the highest height, the initial potential energy the box has is equal to all its mechanical energy. But we also know that the potential energy at point  $h$  is  $mgh$ , so we could express that as:

$$PE_h = mgh$$



Now, how can you express the kinetic energy ( $KE_0$ ) the box has at point 0?



We already know that kinetic energy is equal to this:

$$KE_0 = \frac{1}{2}mv^2$$



Exactly! And we know that kinetic energy at  $h = 0$  must equal the potential energy at point  $h$ :

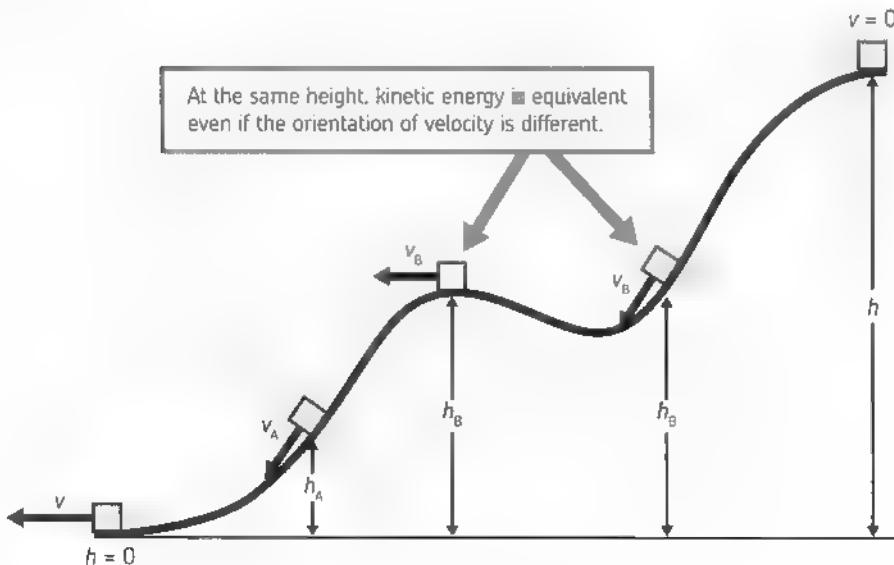
$$PE_h = KE_0$$

But furthermore, due to the conservation of energy, we know that the sum of the mechanical energy must stay the same at all intermediate points on this slope. That is:

$$KE_A + PE_A = KE_B + PE_B$$

$$\frac{1}{2}mv_A^2 + mgh_A = \frac{1}{2}mv_B^2 + mgh_B$$

And this also implies that the potential energy is equivalent at two points of the same height, like point B in the figure. At these two points, the box's kinetic energy is equivalent, even if the orientation of its velocity is different.





Kinetic energy is not associated with the orientation of velocity!



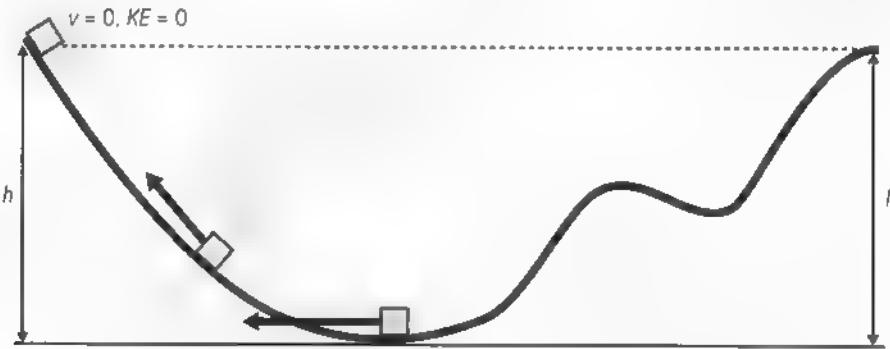
Yes, sir! Er, ma'am. Kinetic energy only has a magnitude. Similarly, potential energy only depends on height.

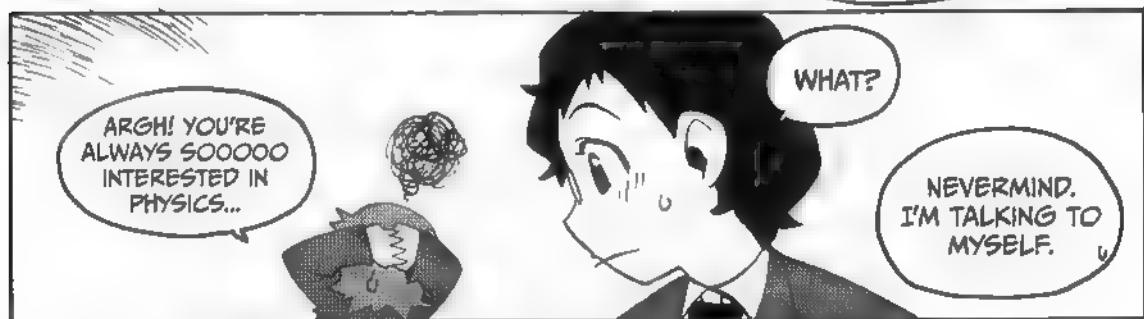
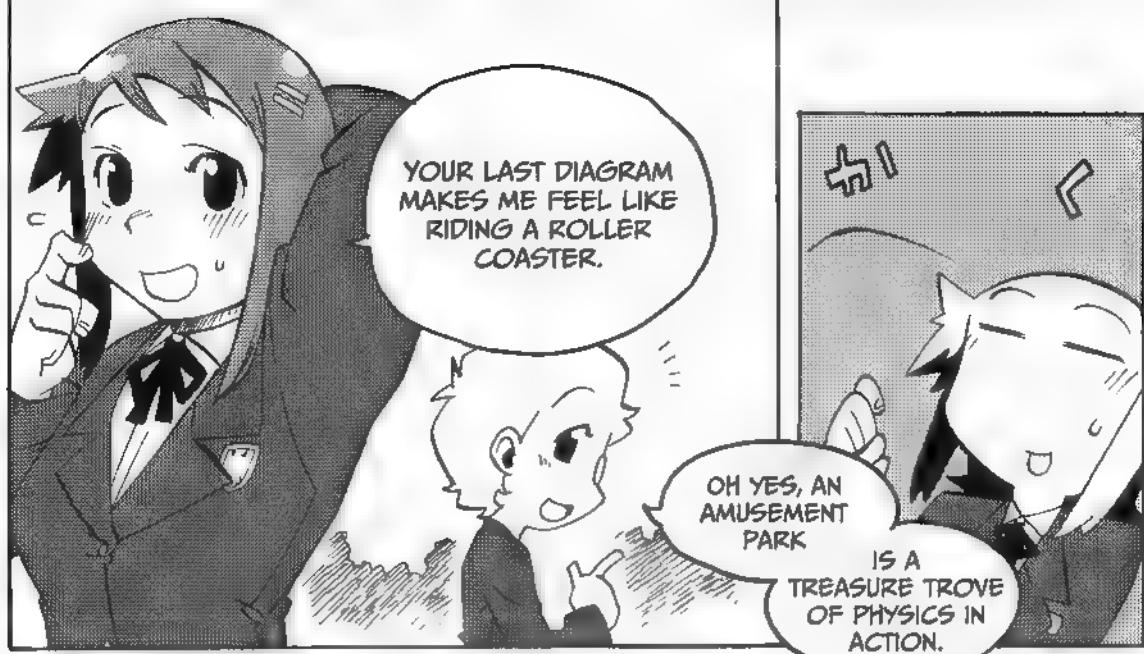


If we extended this slope, would it be possible for the box to go back up to its original height again?



Yes, it would be possible, provided that friction and air resistance are negligible. Of course, it'd be impossible to go beyond that original height of  $h$ .







## UNITS FOR MEASURING ENERGY



The units for energy can be found by applying the definition of mechanical energy, which is as follows:

$$\text{kinetic energy} = \frac{1}{2} \times \text{mass} \times (\text{speed})^2$$

From the expression above, we find the following:

$$\text{units for energy} = \text{units for mass} \times \text{units for speed} \times \text{units for speed}$$

$$1 \text{ joule} = \text{kg} \times \text{m}^2 / \text{s}^2$$

**NOTE** As  $\frac{1}{2}$  does not affect the units, you can omit it when determining the units.

Since energy is a very common physical quantity, a special unit, the *joule* (J), is assigned to it. On the other hand, given the fact that the variation in kinetic energy equals the work done (which we learned on page 176), the following is true:

$$\text{units for energy} = \text{units for work}$$

Therefore, the following expression is also true:

$$\text{units for work} = \text{units for force} \times \text{units for distance} = (\text{N}) \times (\text{m}) = (\text{N} \times \text{m})$$

At first glance, this unit, ( $\text{N} \times \text{m}$ ), looks different from a joule ( $\text{kg} \times \text{m}^2/\text{s}^2$ ). However, recall that a newton (N) is simply equal to  $1 \text{ kg} \times \text{m/s}^2$ . So by multiplying force and distance, we do indeed have the same unit.

To get an idea about how much energy is represented by 1J, it is useful to keep in mind that 1J equals 1 ( $\text{N} \times \text{m}$ ). In other words, you can say, "1J represents energy generated from work that moves an object by 1 m and continues to impose a force of 1N on it."

Additionally, given that the force of gravity on an object with mass of 1 kg is 9.8N, the mass of an object under exactly 1N of gravity is  $1 / 9.8 \text{ kg} = 0.102 \text{ kg} = 102 \text{ g}$ . This is what I meant when I said, "One joule is equivalent to the energy required to lift a 102 g object directly upward 1 meter" (on page 161).

Besides the joule, another common unit for measuring energy is the *calorie* (cal), which is used for thermal appliances such as heaters and food. One calorie (1 cal) represents the thermal energy required for increasing the temperature of one gram of water by  $1^\circ\text{C}$  under one atmosphere of pressure (1 atm). Relative to a joule, this unit is defined as follows:  $1 \text{ cal} = 4.2 \text{ J}$ .

When talking about food, the *kilocalorie* (kcal) is used. One kilocalorie is defined as 1,000 calories. Although the term *calorie* is used informally when talking about food and diet, the scientific unit being referred to is in fact the kilocalorie.

For example, the energy in 50 g of ice cream is about 100 kcal. If you convert it into joules, you get the following:

$$100 \text{ kcal} = 100000 \text{ cal} = 4.2 \times 100000 \text{ J} = 420000 \text{ J}$$

It seems like quite a high value, but it isn't really, if you compare it to the amount of energy we need to survive. According to data from the Japanese Ministry of Health, Labor and Welfare, the daily energy requirement is about 2,200 kcal for a 17-year-old female and about 2,700 kcal for a 17-year-old male. Kilocalories are converted into joules like this:

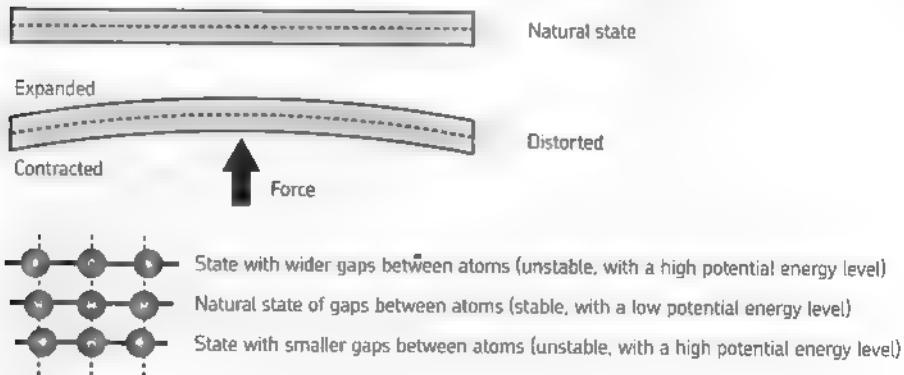
$$2200 \text{ kcal} \times 1000 \text{ cal/kcal} \times 4.2 \text{ J/cal} = 9240000 \text{ J}$$

Let's see how much that is. Since the energy required to lift a load with mass of 1 kg one meter is 9.8J, that value is nearly the amount of energy required to lift a mass of one million kilograms just one meter! That indicates we need a tremendous quantity of energy every day in order to maintain life.

## POTENTIAL ENERGY

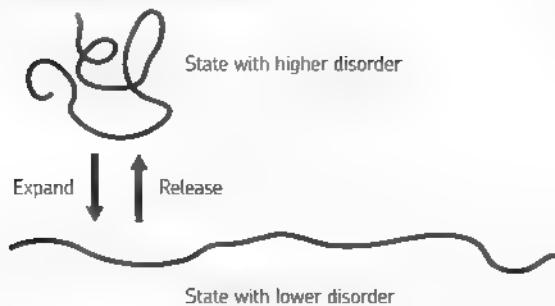
Kinetic energy resides in an object in motion. In contrast, potential energy is not stored inside an object—it's usually energy that comes from an object's position. Typical forms of potential energy include gravitational potential energy and the potential energy of an electrostatic field, which provides the attractive and repulsive force of electricity.

You can also regard the elastic energy of springs and rubber as a form of potential energy. However, different factors are involved in storing this potential energy in different materials. The resilience of springs comes from the spring's contraction to its original state—a spring wants to recover its stable initial position after gaps between atoms (dependent on the potential energy of the electrostatic field working among atoms) are slightly displaced. A coil-type spring used in the real world is designed to transform minor distortion occurring on a straight metal rod into greater displacement by adopting a coiled shape.



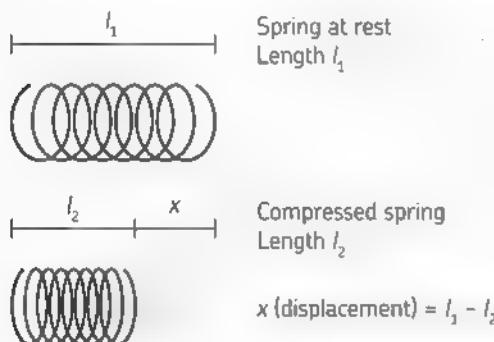
On the other hand, the elasticity of rubber originates in the activity of polymer molecules to recover the initial state with a greater "disorder," where they are very closely curled up, after a state with a lower "disorder," in which molecules are expanded and aligned.

Polymer molecules of rubber



## SPRINGS AND THE CONSERVATION OF ENERGY

Let's think about resilience of a spring as an example of the conservation of energy.

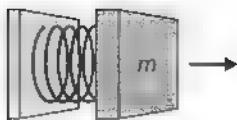


When you compress\* a spring with spring constant  $k$  (you can think of  $k$  as a measure of how springy your spring is in N/m) by  $x$  (the distance beyond its natural length), the potential energy stored in the spring can be expressed as follows:

$$PE = \frac{1}{2}kx^2$$

This stored energy is called *elastic potential energy*. If we place a mass  $m$  next to this spring and the opposite side is fixed, what is the force it will receive? And what will its velocity be?

\* Note that springs work the same way if you stretch them, as well. These equations will hold true in cases of stretching and compression.



The spring wants to return to its natural state and will exert a force on mass  $m$ .

Well, we know that due to the conservation of energy, that mass's kinetic energy must be equal to the spring's potential energy. That means that the following must hold true:

$$PE_{\text{spring}} = KE_{\text{mass}}$$

$$\frac{1}{2}kx^2 = \frac{1}{2}mv^2$$

Solving for  $v$ , we get:

$$v = \sqrt{\frac{kx^2}{m}}$$

**WARNING:  
CALCULUS  
AHEAD!**



Also, as the spring expands, we know that the object is subject to force:

$$F = \frac{-d}{dx}\left(\frac{1}{2}kx^2\right) = -kx$$

Without saying, calculation of work done when the spring with resilient force  $F = -kx$  expands by amount  $x$  relative to its natural length gives us the following:

$$W = \int_0^x (-kx)dx = \frac{1}{2}kx^2$$

This matches potential energy. This is only reasonable, given the conservation of energy.

## VELOCITY FOR THROWING UPWARD AND HEIGHT ATTAINED



On page 194, in response to Megumi's question about how high a ball would go if it was thrown with an initial velocity of 100 km/h, I answer that it is 39 m.

Let's find out why. Given that we know that the following equation holds, you can solve for  $h$ , the height attained by the object thrown:

$$v_1^2 = 2gh$$

$$h = \frac{v_1^2}{2g}$$

Now, plugging in some real numbers for this, we know that 100 km/h equals the following:

$$100 \frac{\text{km}}{\text{h}} = 1000 \frac{\text{m}}{\text{km}} \times \frac{1 \text{ h}}{3600 \text{ s}} = 27.78 \frac{\text{m}}{\text{s}}$$

Now let's put that value into our equation and see what we find:

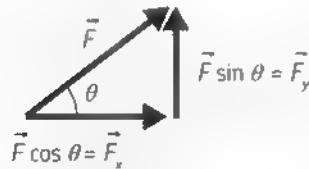
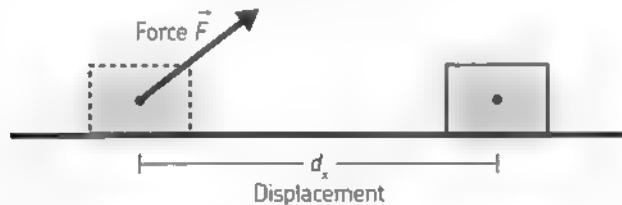
$$h = \frac{v_1^2}{2g}$$

$$h = \frac{27.782}{2 \times 9.8 \text{ m/s}^2}$$

$$h = 39.36 \text{ m}$$

## THE ORIENTATION OF FORCE AND WORK

As you know, we represent work in terms of force and the distance (or the displacement) a force is applied to an object. Let's consider an object being moved over displacement  $d$ , undergoing a force  $\vec{F}$  as shown below.



When the orientations of force and displacement do not match, we must take this into account. In the example above, work ( $W$ ) is represented as follows:

$$W = \vec{F}_x d_x + \vec{F}_y d_y$$

We've split the forces and displacements into their horizontal (x) and vertical (y) components. However, in this case, we know that the vertical displacement of the box is 0, as the

box is moving on level ground. Therefore, we can neglect that term in our calculation of the total work done on the box:

$$W = \bar{F}_x d_x$$

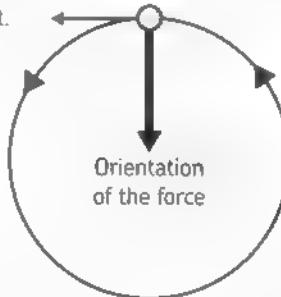
$$W = \bar{F} \cos \theta \times d_x$$

It's also worth noting that we just performed a dot product. So . . . what's that? Well, work and energy are scalars—they have no orientation. But force and displacement are both vectors, as they have an orientation. The multiplication of two vectors in this way is called a *dot product*.

In a case where the force is in a direction opposite to the displacement, the work is said to be negative. This kind of work results in a deceleration.

Additionally, when the orientation of force is perpendicular to the displacement, given that  $\cos 90 = 0$ , no work is done. A typical case in which the orientation of force is perpendicular to that of displacement is uniform circular motion. While force is working toward the center of the circle (centripetal force), kinetic energy does not change because the value of work is zero. Because of this, an object can move in a circular direction at a uniform speed.

The orientation of the velocity matches that of the displacement.



## FINDING AN AMOUNT OF WORK WITH NONUNIFORM FORCE (ONE-DIMENSIONAL)

### WARNING: CALCULUS AHEAD!



In the case of a uniform force, we can express work as the product of the displacement and the force in the direction of the displacement. But many times, forces are not constant.

To deal with nonuniform forces, we can break up the force into short segments. If we break it up into tiny enough pieces, we can say the force is constant during each segment. We can look at any one of these segments, which we will label with a subscript  $i$ , and the work can still be expressed as the product we have seen before:

$$\frac{1}{2}mv_{,i}^2 - \frac{1}{2}mv_i^2 = F\Delta x$$

Of course, this is true for every segment  $i$ , so we can add up all of these to find the work done across the entire displacement, from  $x_1$  to  $x$ :

$$\left(\frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2\right) + \left(\frac{1}{2}mv_3^2 - \frac{1}{2}mv_2^2\right) + \left(\frac{1}{2}mv_4^2 - \frac{1}{2}mv_3^2\right) + \dots = \\ F_1\Delta x + F_2\Delta x + F_3\Delta x + \dots$$

By looking closely at the left-hand side, you can see that most of the terms will cancel! We are left with just two terms:

$$\frac{1}{2}mv_n^2 - \frac{1}{2}mv_1^2$$

So we can rewrite this equation as:

$$\frac{1}{2}mv_n^2 - \frac{1}{2}mv_1^2 = \sum_{i=1}^n F_i\Delta x$$

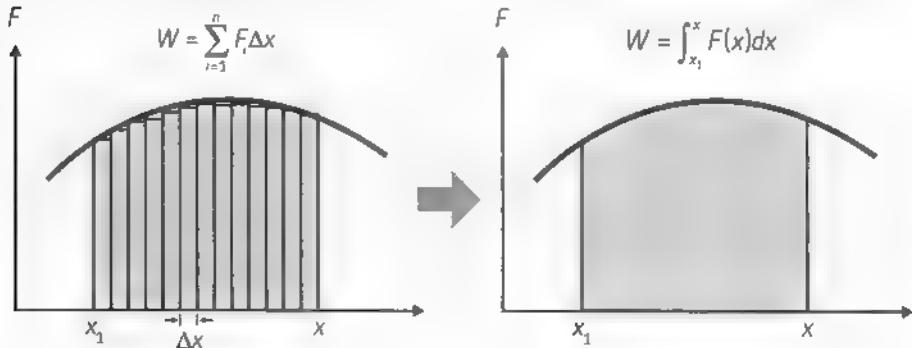
We have added up the little pieces of work done at each instant to get the total change in energy—the work  $W$ . You'll see that this looks awfully similar to the definition of an integral. It turns out that if we make the sections infinitely small by making  $n$  go to infinity, then we can change the summation to an integral by the rules of calculus:

$$W = \lim_{\substack{\Delta x \rightarrow 0 \\ n \rightarrow \infty}} \sum_{i=1}^n F_i\Delta x$$

$$W = \int_{x_1}^x F(x)dx$$

**NOTE**  $F$  here does not denote a function. Remember, that  $F$  stands for force!

This is much easier to see graphically, as all we are doing is adding up the area under the curve on a plot of  $F$  vs.  $x$ . An integral is exactly this, in the limit of making the width of the segment go to zero.



In conclusion, the statement, the change in kinetic energy between two points is equivalent to the work done on the object within that segment, means the following:

$$W = \int_{x_1}^x F(x)dx$$

When the above is assumed, the statement can be expressed as:

$$\frac{1}{2}mv^2 - \frac{1}{2}mv_0^2 = W$$

Note that  $v$  in the equation above equals the object's final velocity,  $v_f$ .

## NONCONSERVATIVE FORCE AND THE LAW OF CONSERVATION OF ENERGY



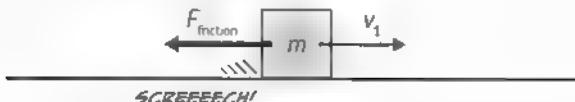
Not all forces can be expressed as having a potential. Forces such as these are said to be *nonconservative*. Friction is a typical nonconservative force. When a nonconservative force is doing work, the energy of a system goes down. For example, if you push a book across a table, it will slide to a stop. This doesn't mean that energy is not conserved—just that it went somewhere that you can't easily get it back. For example, the book gave kinetic energy to the molecules of the table in the form of heat.

### FRICITION: A NONCONSERVATIVE FORCE

Now let's examine the force of friction, an example of a nonconservative force. First, let's assume a mass of  $m$  is in motion with velocity  $v_1$ .

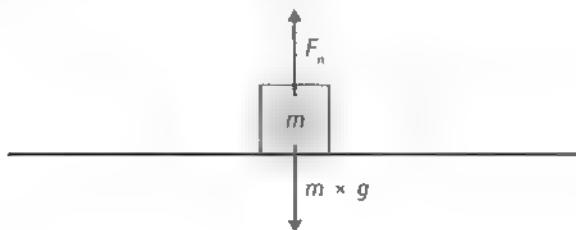


If the object had no forces working on it, it would continue to travel with velocity  $v_1$  forever—that's just Newton's first law in action. But life isn't so simple. Let's assume this object's motion is impeded by the force of friction between the bottom of the object and the surface that it's traveling on.



The magnitude of this force depends on two factors: the normal force and the coefficient of friction. But what are those, you ask? Well, the *normal force* is simply the force *perpendicular* to the surface a body travels on. The larger an object's mass, the larger the normal force, and the larger the force of friction itself. In the example above, the normal

force is simply the weight of the mass, ( $F = ma$ , so in this case,  $F_{\text{normal}} = m \times g$ ). We'll look at a more complicated example of normal forces shortly to see how the normal force differs from the weight of an object.



The *coefficient of friction* is simply a measure of how "sticky" two surfaces are. Rubber on concrete, for example, has a very high coefficient of friction. But the coefficient of friction between ice and an ice skate is very low. We use the following formula to determine the frictional force working on an object:

$$F = \mu \times F_n$$

$$\text{force of friction} = \text{coefficient of friction} \times \text{normal force}$$

Since  $F = ma$ , we know that the normal force is simply the mass times the acceleration due to gravity. That is,  $F_n = m \times g$ :

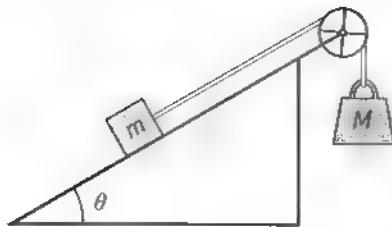
$$F = \mu \times m \times g$$

The variable  $\mu$  we use to represent the coefficient of friction is the Greek letter mu (pronounced "mew"). Scientists can determine the coefficient of friction of two objects through direct observation and experimentation. The coefficient of friction ranges from very close to zero to greater than one.

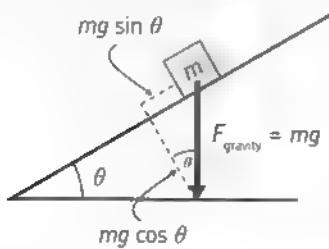
But wait, how do we determine the direction of that frictional force? And what happens when the object finally comes to rest? Well, let's use common sense: Friction works to oppose motion. It's always in the opposite direction of velocity or an imposed force (including cases when the object is at rest). And the equation above isn't true in every case. This is simply the *maximum possible force* exerted by friction on the object. When it's at rest with no outside forces imposed, there will be no frictional force. Friction won't move the object backwards, of course!

## FRICTION ON A SLOPE

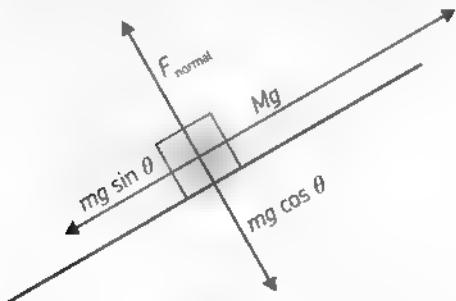
Now let's consider a more complicated scenario. A small mass of  $m$  is on a ramp with angle  $\theta$ . The mass  $m$  is attached to a larger mass  $M$  by a rope, which exerts a force on the smaller mass, in a direction parallel to the ramp.



If there are no other forces to consider, the only forces on mass  $m$  are the force of gravity,  $m \times g$ , and the force of the tension of the string,  $M \times g$ . To determine the acceleration of the mass  $m$ , we'll decompose the force of gravity into a force that opposes the direction of motion (that is, one parallel to the direction of the ramp and the tension of the rope attached to mass  $M$ ), and a force perpendicular to the ramp itself.



We know that the right triangle formed by the decomposition of this force is similar to the triangle formed by the ramp (that is, it has the same angle,  $\theta$ ). This means that the force opposing the tension of the rope is equal to  $mg \sin \theta$ . The force that's perpendicular to the ramp and the motion of mass  $m$  is equal to  $mg \cos \theta$ . If there's no friction at work, we can ignore this force, as it's offset by a force perpendicular to it, imposed by the ramp itself. This is simply Newton's third law in action.



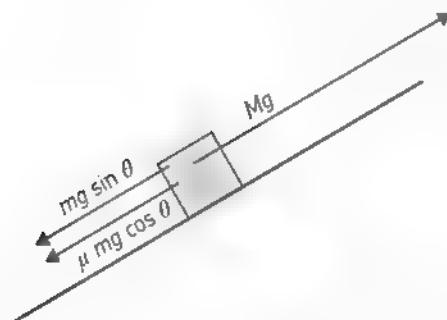
Now that we know all this, can you determine how this system works if we take into account the friction between mass  $m$  and the ramp? First, let's think about the normal force. Earlier, I said that it's the force perpendicular to the surface. That means that the force of the object perpendicular to the ramp,  $mg \cos \theta$ , is equal to our normal force. The force of friction for this object is as follows:

$$F_{\text{friction}} = \mu mg \cos \theta$$

Taking into account all forces on the object parallel to the ramp ( $mg \cos \theta$  is offset by the normal force), we have the following relationship:

$$F_{\text{net}} = Mg - mg \sin \theta - \mu mg \cos \theta$$

net force = tension of the rope - component force of gravity - force of friction



Knowing all this, we can determine how quickly object  $m$  will accelerate up the ramp!

## COLLIDING COINS AND THE CONSERVATION OF ENERGY

**WARNING:  
SERIOUS  
ALGEBRA  
AHEAD!**

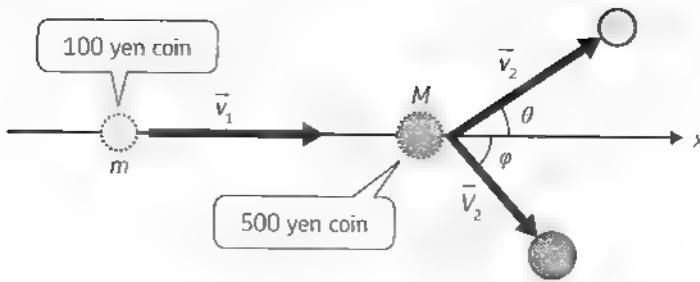


In Chapter 3, we examined collision of coins, the conservation of momentum, and how it must hold true in two dimensions (page 144). In this example, we know that the 100 yen coin's initial momentum in the  $x$  direction must match the final momentum of both coins in the  $x$  direction. In the following equations the 100 yen coin has mass  $m$  and the 500 yen coin has mass  $M$ :

$$\textcircled{1} \quad mv_1 = mv_2 \cos \theta + MV_2 \cos \varphi$$

And because the 100 yen coin has no initial momentum in the  $y$  direction, we know that the momentum of both coins in the  $y$  direction must offset each other:

$$\textcircled{2} \quad 0 = mv_2 \sin \theta - MV_2 \sin \varphi$$



Assuming that this is a completely elastic collision (that is, kinetic energy is conserved), we also know the following:

$$\text{initial kinetic energy} = \text{final kinetic energy}$$

$$\textcircled{1} \quad \frac{1}{2}mv_1^2 = \frac{1}{2}mv_2^2 + \frac{1}{2}MV_2^2$$

For these three equations (1, 2, and 3) we have four unknowns— $v_2$ ,  $V_2$ ,  $\theta$ , and  $\phi$ . It's not possible to find exact solutions, since we have too many variables to solve for and not enough equations. However, we can explore the relationships between these variables. So let's examine the 100 yen coin and the relationship between the ratio of its initial and final velocity ( $v_2 / v_1$ ) to the subsequent scattering angle ( $\theta$ ). For simplicity, we'll assume that  $m < M$ . (The collision of the 100 yen and 500 yen coins satisfies this condition.)

First, let's solve our equations to get rid of the variable  $\phi$ . We'll solve for  $\sin \phi$  and  $\cos \phi$  for simplicity's sake. First, let's consider equation 1, where it looks like we can easily solve for  $\cos \phi$ :

$$\textcircled{1} \quad \begin{aligned} MV_2 \cos \phi &= mv_1 - mv_2 \cos \theta \\ \cos \phi &= \frac{mv_1 - mv_2 \cos \theta}{MV_2} \end{aligned}$$

Now let's solve for  $\sin \phi$  in equation 2:

$$\textcircled{2} \quad \begin{aligned} MV_2 \sin \phi &= mv_2 \sin \theta \\ \sin \phi &= \frac{mv_2 \sin \theta}{MV_2} \end{aligned}$$

With these two relationships in hand, we can substitute these equations (1) and (2) into a basic trigonometric relationship, which holds true for any angle:

$$\textcircled{3} \quad \sin^2 \phi + \cos^2 \phi = 1$$

Be warned that the algebra required in this section is tricky! After solving for  $V_2^2$ , you should get the following:

$$\textcircled{4} \quad V_2^2 = \left(\frac{m}{M}\right)^2 (v_1^2 - 2v_1v_2 \cos \theta + v_2^2)$$

We know energy has been conserved, so we know that equation ❸ must hold true. So let's substitute equation ❷ into equation ❸. Then we'll only have three variables to consider:  $v_1$ ,  $v_2$ , and  $\theta$ , just as we wanted. Try solving for  $v_2$ . (Hint: You may need to use the quadratic formula.)

After all your work, you'll discover the following relationship:

$$\textcircled{3} \quad v_2 = \frac{\left(\frac{m}{M}\right)\cos\theta + \sqrt{1 - \left(\frac{m}{M}\right)^2 \sin^2\theta}}{1 + \frac{m}{M}} v_1$$

Additionally, assign  $\theta = 0$  for this expression, and you'll find  $v_1 = v_2$ . This is relevant to a case where object 1 passes by object 2 without colliding.

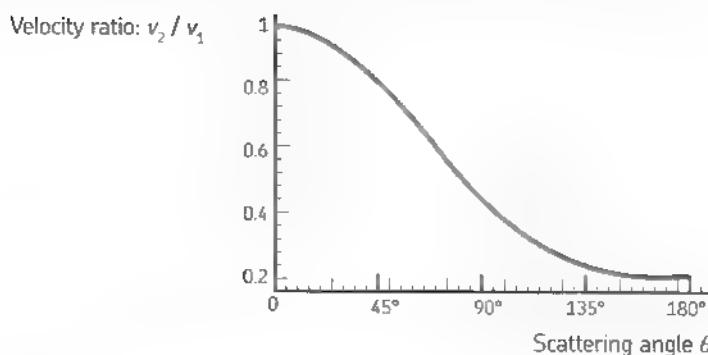
On the other hand, assuming a case where the objects bounce back in opposing directions and  $\theta = 180^\circ$ , you get the following:

$$\textcircled{4} \quad v_2 = \frac{1 - \frac{m}{M}}{1 + \frac{m}{M}} v_1$$

This equation indicates that as mass  $M$  becomes much larger than mass  $m$ , the following relationship holds true:  $v_2 = v_1$ . (This is because the term  $(m / M)$  approaches zero.) This means that an object with smaller mass having a head-on collision with a huge object bounces back at the same velocity it had before it hit the larger object. On the other hand, when  $M = m$ ,  $v_2 = 0$ . You can reconfirm this relation by causing a head-on collision of two 100 yen coins by replacing the 500 yen coin with another 100 yen coin, taking care not to allow an oblique course. After the collision, the 100 yen coin halts and the other 100 yen coin previously in a stationary state starts traveling at the same speed. In this case, we can easily find that  $v_2 = v_1$  from equation ❸. The two coins essentially swap velocities.

Now let's plot on a graph the relationship between the scattering angle ( $\theta$ ) and the velocity ratio  $v_2 / v_1$  for the 100 yen coins before and after the collision. Since the mass of a 100 yen coin is 4.8 g, while that of a 500 yen coin is 7.0 g, we get  $m / M = 4.8 / 7.0 = 0.69$ . We'll use this result in equation ❸, then solve for  $v_2 / v_1$ , and plot the results. Here's the actual equation that we'll graph:

$$\textcircled{5} \quad \frac{v_2}{v_1} = \frac{0.69\cos\theta + \sqrt{1 - 0.69^2 \sin^2\theta}}{1 + 0.69}$$



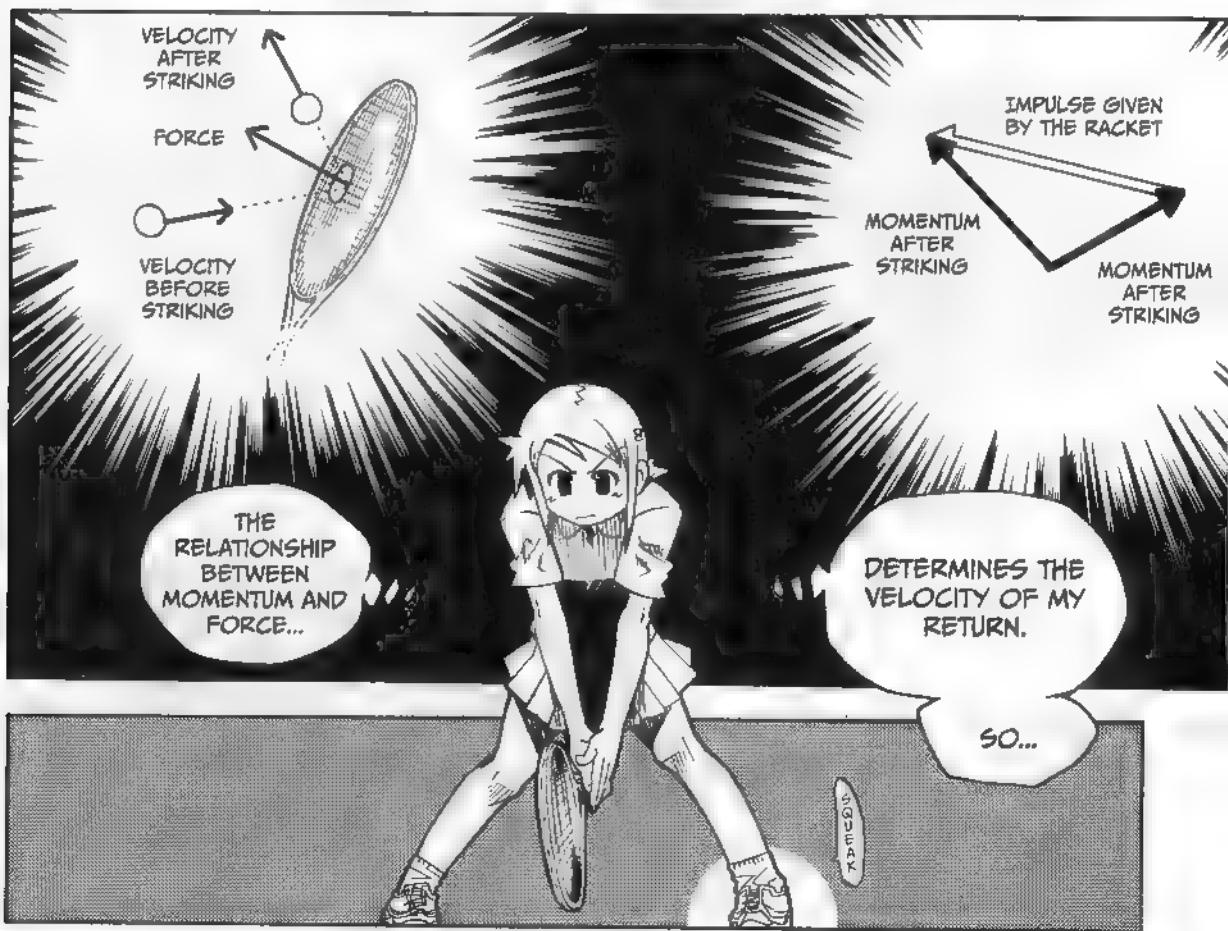
This graph should make intuitive sense to you after some consideration. If the scattering angle is greater (that is, the coins' collision is a glancing strike), the secondary velocity of the coin ( $v_2$ ) will be smaller, thus the relationship of  $v_2 / v_1$  will be smaller as well. Note that if you use objects of different masses, this relationship (and the graph that represents it) will change.



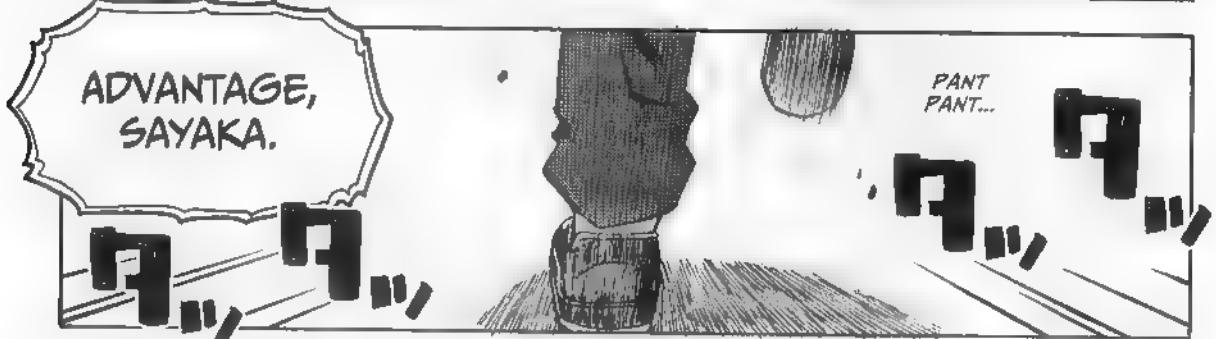
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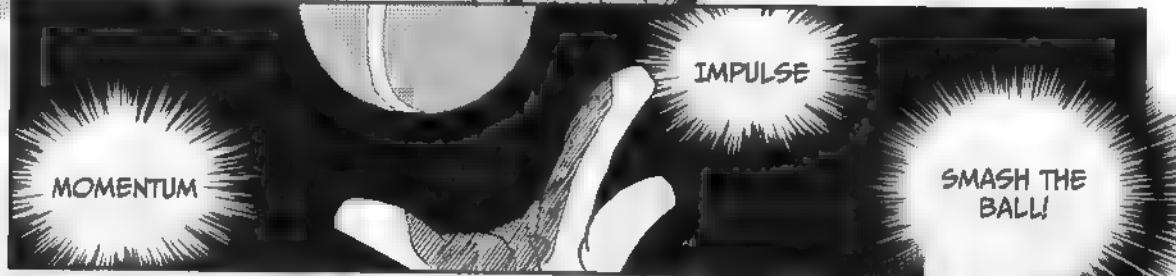
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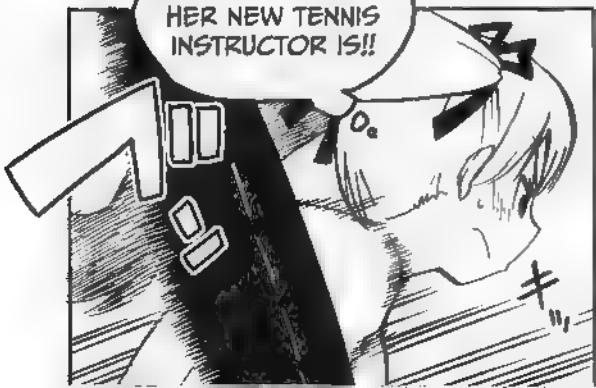
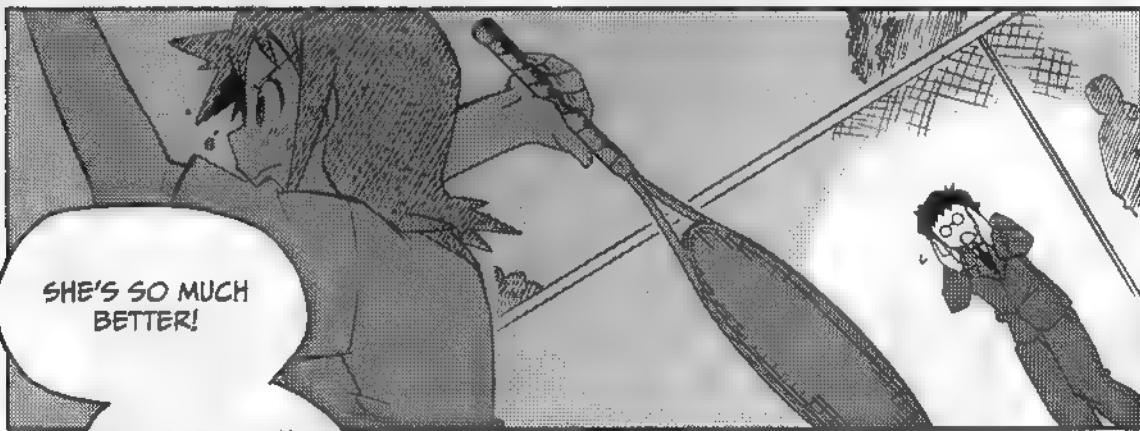
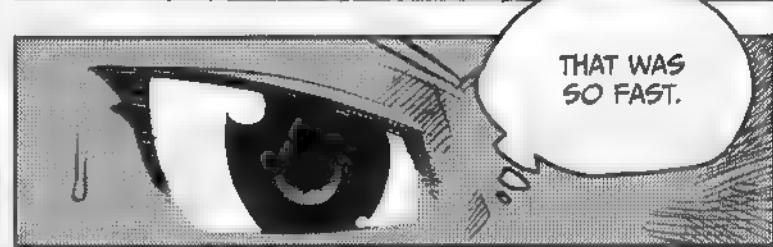
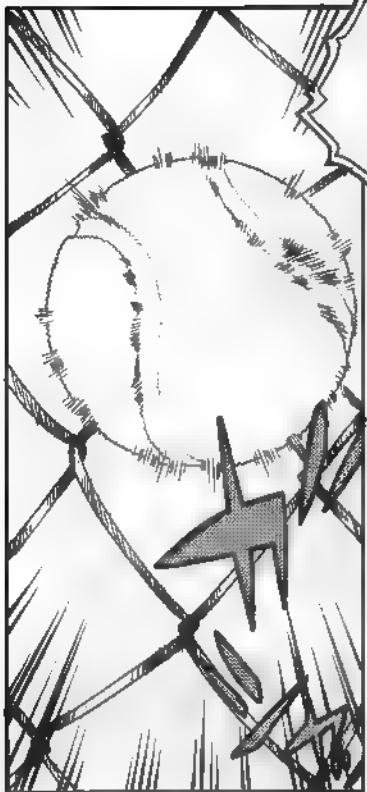


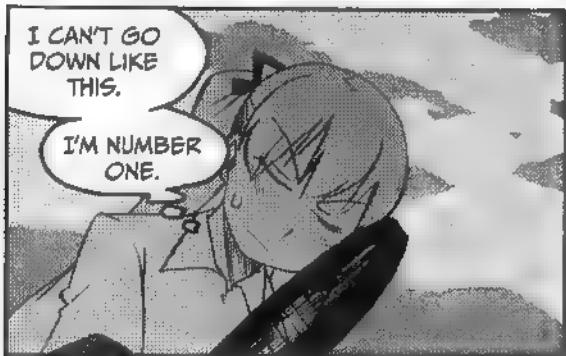
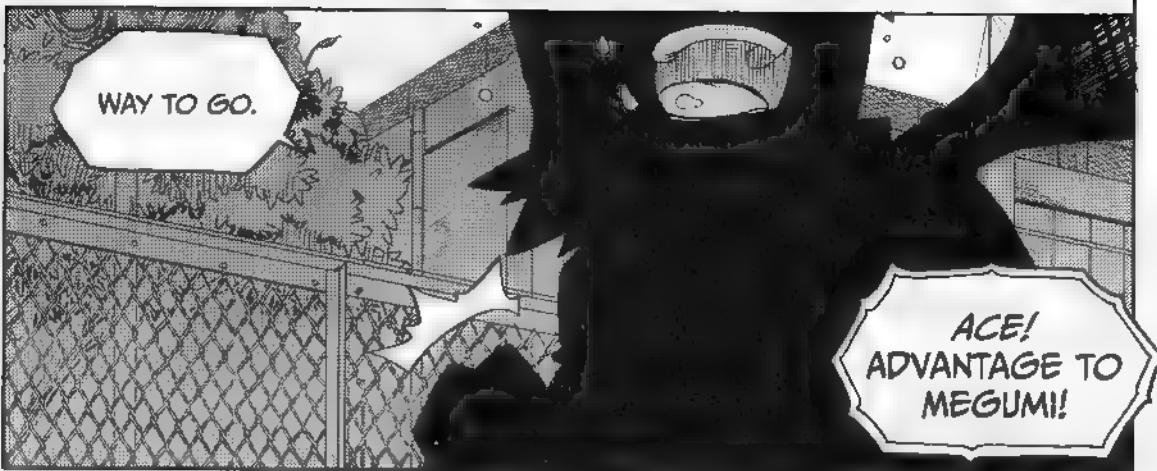








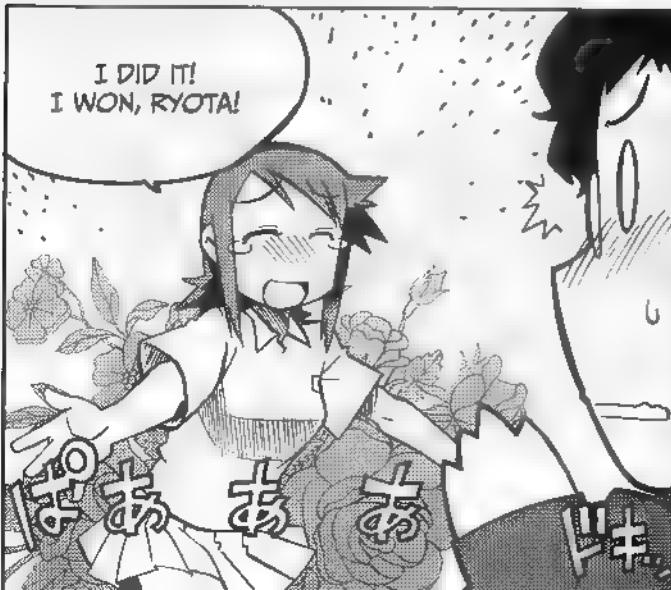




I REMEMBER  
YOUR LESSONS  
PERFECTLY,  
RYOTA.

MAKE MY BODY  
FLEXIBLE.

MAXIMIZE FORCE  
WHEN THE RACKET  
STRIKES THE BALL!



HEY, YOU!

YOU CAN'T GET AWAY FROM ME, YOU KNOW.

UM...

AHEM.  
WILL YOU BE MY PARTNER FOR THE  
NEXT DOUBLES MATCH?

SURE,  
IT'S A DONE DEAL.

YOU KNOW RYOTA,

THIS FEELS LIKE  
A FORCE OF  
ATTRACTION.

PERHAPS  
IT IS...

WHAT ARE YOU  
TWO TALKING  
ABOUT?!

# MAKING SENSE OF UNITS

When it comes to classical mechanics, there are only three *base units*. Using these three simple measurements, you can derive more complicated units of measure like the newton and the joule. The three base units are as follows:

meters, m

(which measure *distance*)



seconds, s

(which measure *time*)



kilograms, kg

(which measure *mass*)



## VELOCITY AND ACCELERATION

Let's explore how we can combine these three units to derive new ones. First, let's explore velocity and acceleration:

$$\text{velocity} = \frac{\text{change in distance (m)}}{\text{time (s)}} = \text{m/s}$$

$$\text{acceleration} = \frac{\text{change in velocity (m/s)}}{\text{time (s)}} = \text{m/s}^2$$

Given these relationships, you can see that *velocity* is defined as a change in distance, and *acceleration* is simply the change of that change! Students of calculus know that this means that velocity is the *first* derivative of distance, and acceleration is the *second* derivative of distance (both with respect to time).

## FORCE

Given Newton's second law, we know force equals mass times acceleration ( $F = ma$ ):

$$\text{force} = \text{mass (kg)} \times \text{acceleration (m/s}^2) = \text{kg} \times \text{m/s}^2 = \text{N}$$

To save ourselves a headache, we call a  $\text{kg} \times \text{m/s}^2$  a *newton* (N). Remember this relationship, as it will be important in deriving other units!

$$1 \text{ kg} \times \text{m/s}^2 = 1 \text{ N}$$

## MOMENTUM AND IMPULSE

*Momentum* is an important physical quantity to measure, especially when considering collisions, landings, and impact. It is defined as:

$$\text{momentum} = \text{mass (kg)} \times \text{velocity (m/s)} = \text{kg} \times \text{m/s}$$

*Impulse*, as you've already read in Chapter 3, is just a change in momentum, and it can be calculated like so:

$$\text{impulse} = \text{force (N)} \times \text{time (s)} = \text{kg} \times \text{m/s}$$

Why does this calculation work? Remember that  $1\text{N} = 1\text{kg} \times \text{m/s}^2$ . Note that the unit for momentum,  $\text{kg} \times \text{m/s}$ , has no shorter name.

## ENERGY AND WORK

*Kinetic energy* is defined like so:

$$\text{kinetic energy} = \frac{1}{2} \times \text{mass (kg)} \times \text{velocity}^2 (\text{m/s}) = \text{kg} \times \text{m}^2/\text{s}^2 = \text{J}$$

Just as we did with force, we'll use a simpler name for the unit of energy—the *joule* (J), which is named after English physicist James Prescott Joule. *Gravitational potential energy* can be calculated like this:

$$\text{potential energy} = \text{weight (N)} \times \text{height (m)} = \text{kg} \times \text{m}^2/\text{s}^2 = \text{J}$$

And naturally, our units match those of kinetic energy. *Work* is a measure of the energy transferred by a force over a distance. Notice the similarities in this equation to the previous one:

$$\text{work} = \text{force (N)} \times \text{distance (m)} = \text{kg} \times \text{m}^2/\text{s}^2 = \text{J}$$

The result of all these calculations is the joule, our unit for energy—just as it should be!

## SI PREFIXES

You can add a prefix to a unit in order to increase or decrease its magnitude. These prefixes for different powers of 10 are called *SI prefixes*, and they come from internationally determined rules for units called the International System of Units (SI units). For example, 1 kilometer (km) is equal to 1,000 meters, 7 megajoules (MJ) are equal to 7,000,000 joules, and 3 nanograms (ng) are equal to 0.000 000 003 grams.

**NOTE** The symbols for prefixes higher than *kilo* are capitalized.

Symbol	Name	Power of ten
y	yocto-	$10^{-24}$
z	zepto-	$10^{-21}$
a	atto-	$10^{-18}$
f	femto-	$10^{-15}$
p	pico-	$10^{-12}$
n	nano-	$10^{-9}$
$\mu$	micro-	$10^{-6}$
m	milli-	1/1000
c	centi-	1/100
d	deci-	1/10
da	deka-	10
h	hecto-	100
k	kilo-	1000
M	mega-	$10^6$
G	giga-	$10^9$
T	tera-	$10^{12}$
P	peta-	$10^{15}$
E	exa-	$10^{18}$
Z	zeta-	$10^{21}$
Y	yotta-	$10^{24}$



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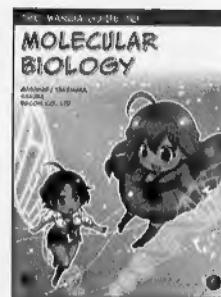
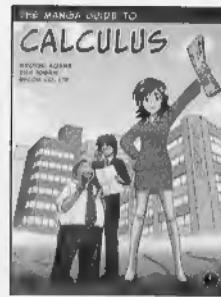
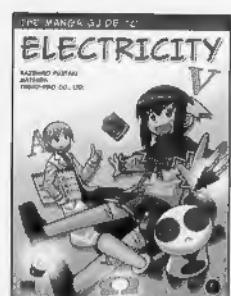
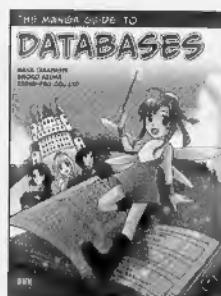
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